ON FREQUENCY CONTROL PROVISION WITH A MICROGRID CONTAINING BATTERY ENERGY STORAGE SYSTEMS AND RENEWABLE ENERGY SOURCES

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ABSTRACT

The main benefit of operating a distribution grid as a microgrid (MG) is the additional security of supply due to its local electricity generation and islanding possibility. In this work, we investigate the technical ability and the economic viability of a MG with renewable generation to provide also frequency control (FC) to upper voltage levels as an additional source of revenue in grid-connected mode. To compensate for the variable generation of renewable energy sources and facilitate opportunities to bid in FC markets, we include a battery energy storage system (BESS). In order to determine the potential of the MG in the different FC markets, the problem is formulated as a multi-period optimal power flow with a rolling horizon of 24 hours. In order to evaluate the business case for such a system, we carry out an ex-post analysis in which we include the investment cost of a BESS and determine the life cycle benefits using the revenue streams calculated by the proposed optimization scheme.

I. INTRODUCTION

A microgrid (MG) is a small network of electricity users and local generation that is usually connected to the main grid, but can also be operated independently. It is able to integrate and coordinate the actions of all users in an intelligent fashion. The main advantage of a MG is the enhanced reliability of power supply for its connected customers due to its islanding capability in case of external faults. Furthermore, employing renewable distributed energy resources (DER) reduces transmission losses as well as the ecological footprint of electricity usage. However, due to the intermittent nature of distributed renewable energy resources (RES), a local balancing resource such as a battery energy storage system (BESS) is required to ensure the capability of switching to the islanded mode at any time. Installation of a BESS is still relatively expensive and since its energy capacity needs to be dimensioned for the worst-case combination of generation and load forecasts, it is seldom used to its full capacity. Therefore, there is unused battery capacity that can be utilized to generate additional revenue streams. One possibility is the provision of frequency control (FC) to upper grid levels. It is conceivable that the MG participates in any of the three levels of frequency control markets, i.e. providing primary (FCR), secondary (FRRa) and tertiary control power (FRRm).

An increased penetration of renewable DER has and will further increase the demand for FC power due to the unpredictable nature of these generation units. Provision of FC with a MG can therefore not only be a source of income for a Distribution System Operator (DSO), but following the polluter-pays-principle the increased demand for FC caused by the renewables in the MG would be covered by the MG itself.

This paper investigates the provision of services by a MG, comprising of photovoltaic (PV) units, a BESS and controllable loads. In grid-connected mode, it expands existing centralized control schemes to offer FC products under uncertainty within an optimization framework, while in islanded-mode, it ensures the operation of the MG for a predetermined amount of time. Both the technical feasibility, as well as the economic viability are investigated through case studies.

II. METHODOLOGY

At the core of the proposed methodology lies a centralized MG control scheme which optimizes an objective function related to the whole MG. The contribution of the paper comprises the inclusion of constraints for the services provided in both operational states of the MG, and the implementation in a rolling horizon fashion. The algorithm includes an iterative power flow computation adapted from [1] as well as the incorporation of generation forecast uncertainty by employing empirical uncertainty margins as in [1].
An overview of the applied model structure is depicted in Fig. 1 and its individual blocks are briefly described in the subsequent sections.

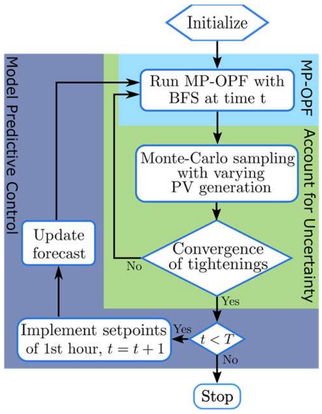

Figure 1: Simplified proposed model structure

Multi-period OPF

In this part, the operational costs as well as the revenues

from a bid in the FC market are optimized from the perspective of a DSO over a forecasting horizon of 24 hours. The exact AC power flow equations are replaced with a single iteration of the Backward-Forward-Sweep (BFS) power flow method, following [1].
As active control measures, we consider curtailment of PV generation, load shifting as well as operation of the BESS. The BESS model takes charging/discharging inefficiencies into account but neglects internal losses.
Furthermore, we permit curtailment of non-critical loads in the islanded mode. To ensure that a minimum amount of load can be served during the initial 24 hours of islanded operation, the expected evolution of the BESS SoC in case of a switch to the islanded mode at any point in time is incorporated.
Included model constraints encompass the operational limits for bus voltages and line currents, limits for reactive power generation/absorption of inverters based on a minimum acceptable power factor, limits for the temporal shifting of load, limits on the battery charging/discharging power and the FC constraints that ensure the reservation of a sufficient amount of power and energy according to the FC bid size. The requirements for each FC product are discussed in detail later. The bid size for FC is treated as an optimization variable in the first time step and kept at the chosen value throughout the remainder of the FC tender period. A detailed description of the mathematical formulation is provided in [2].
The resulting problem is a mixed-integer quadratically constrained program, implemented in MATLAB and solved with the commercial solver Gurobi.

Consideration of uncertainty

Regarding PV generation uncertainty in the operational planning, we consider PV forecast error distributions and formulate chance-constraints for bus voltages and line currents, which should hold with a desired probability. The chance-constraints are transformed into deterministic constraints by bound tightening. The required margins that need to be enforced are derived using a Monte Carlo simulation [1].

Model predictive control

Since PV forecasts are not accurate for a time horizon of one week, which is the usual tender period for FC products, a model predictive control (MPC) structure is applied. A MPC uses the forecast over a finite horizon to optimize a given control problem, implements the optimal control measures for the first time step and updates the forecast. The current state of the system is then taken as the initial condition for the subsequent optimization step. In our case, we used a rolling horizon of 24 hours with a step-length of one hour.

Frequency control constraints

To be able to provide FC, guaranteed power and energy reserves (i.e. a minimum duration of contracted power delivery) are required, that can be requested at any time. These are enforced as constraints in the optimization algorithm. The main part of the reserves will be covered by the BESS. However, it can be supported by up-/down-regulation of PV and load shifting, that both incur a cost penalty. The following sections describe briefly the different prerequisites for each product.

Primary control

FCR is a symmetrical product, requiring an equal amount of regulation power in both directions. Concerning the energy requirement, for a BESS a minimum energy reserve equal to a full FCR dispatch of 15 minutes is demanded. Nevertheless, the limiting factor in terms of FCR bid size for a BESS with an energy-to-power-ratio of one is the power reserve rather than the energy reserve. Only the BESS is considered to provide FCR because the reaction times of shifting loads are too slow and, furthermore, constant switching of these devices is detrimental for their lifetime. Including also the PV units would not yield any additional benefit, since reserved power is the limiting factor for FCR and PV units cannot provide power throughout the day.

Secondary control

Similar to FCR, also FRRa is symmetrical and requires fast reaction times. Load shifting is therefore also unsuitable to provide FRRa. In contrast to FCR, provision of FRRa is not energy neutral, but a successive dispatch in one direction can become somewhat energy intensive (energy requirements of up to 5.5h times the contracted power were observed within 24 hours, analysing past data).
Reservation of such a large amount of energy and hence, being able to respond to a worst-case call at any time would drastically limit the bidding potential for FRRa. Therefore, we follow a less conservative approach, only being able to respond to a worst-case call during the first four hours. After that, the missing/surplus energy could be compensated by taking according actions on the intraday market. The minimum lead time for intraday activities is one hour, allowing enough time to identify the need for such actions. Despite this less conservative energy requirement, the energy reserve is the limiting factor for the bidding potential for this product. To ensure these reserves, such a four-hour worst-case scenario is simulated at every time step in each direction and implemented as an additional constraint in the optimization.

Tertiary control

FRRm products are not symmetrical but split into up- and down-regulation. A call is not a continuous signal, but it is a single event, where only a full dispatch of the contracted power is possible. Partial dispatch is not possible as opposed to FCR and FRRa.
Similar to the previous case, a call scenario with a maximum duration of four hours is simulated at each time step to enforce the necessary power and energy reserve constraints. We omitted the possibility of successive calls as the likelihood of that is small.

III. SIMULATIONS

Test Grid

A modified version of the Cigre LV Benchmark grid [3] is used as test grid (see Fig. 2). Added elements are the

BESS at node 2, as well as PV units at nodes 12, 16, 18 and 19. Each of the nodes 17, 18 & 19 features a flexible share of its load that can be shifted temporally according to the defined constraints.

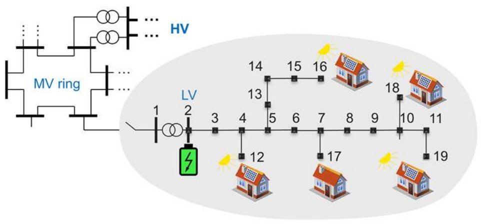

Figure 2: Modified Cigre LV Benchmark grid

Case Studies

In the case studies, we investigate the operational planning of all DERs to assess the bidding potential and their ability to respond to an actual call. In total, 60 case studies with different BESS capacities, ranging from 308 – 572 kWh, were investigated. These values correspond to 1.4 – 2.6 times the needed minimal BESS capacity to allow for islanded operation in the worst-case combination of generation and load (220 kWh). The energy-to-power-ratio of the BESS is kept at one for all case studies. Each case study comprises a single week during spring, summer or winter to account for seasonal characteristics. For simplicity, only the results for a 484 kWh BESS in spring are shown. The case where the MG does not participate in FC markets is referred to as the base case (benchmark).

BESS SoC behaviour

The results are presented in Figs. 3 – 6. In each of these figures a different service is provided. The red areas guarantee the switch into the islanded operation at any time step, by preserving a minimum BESS energy content based on load and generation forecasts. The orange area represents the energy limitation coming from the offered bid size on the FC market. The white area corresponds to the allowable feasible region for the battery state of charge (SoC) at each hour of the simulated week, and the black line the optimization result. In case of overlapping between the orange and red area, the more limiting area is relevant. This approach was chosen as in case of a change into the islanded mode, frequency reserves do not have to (or even cannot) be provided anymore.

FCR reserves

Figure 3 shows the BESS SoC while providing FCR reserves. Given the energy-to-power-ratio of one, an energy requirement of 15 minutes fully contracted FCR power translates into an energy reserve of 50% of the total BESS capacity. The algorithm keeps the SoC at the upper limit to minimize load shedding in case of a switch to the islanded mode.

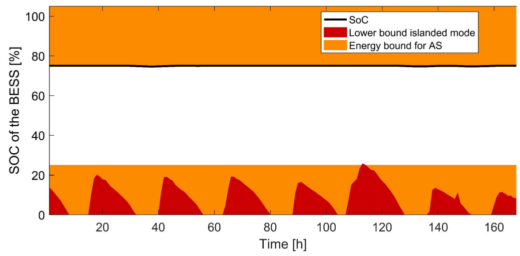

Figure 3: BESS SoC with FCR reserve provision

FRRa reserves

At times, when PV generation is available, it could be curtailed at some cost in order to provide down-regulation. Hence, the energy requirement set aside for down-regulation is temporarily decreased during the daytime compared to nighttime, as seen in Fig. 4. The BESS is then charged during these hours, allowing for a higher self-consumption of the grid and more flexibility in case of a switch to the islanded mode.

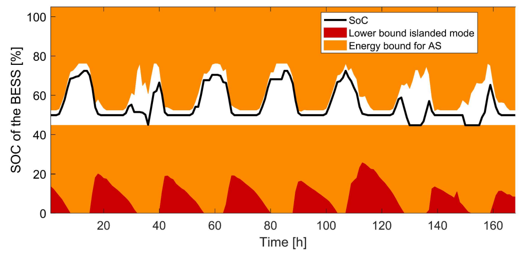

Figure 4: BESS SoC with FRRa reserve provision

FRRm up reserves

It is most favourable to keep the BESS fully charged at any time, allowing for maximum reserve provision as well as minimum load curtailment when switching to islanded mode. The dips in the orange area of Fig. 5 are caused by some variations in flexible loads at these hours, but do not affect the maximum bid size.

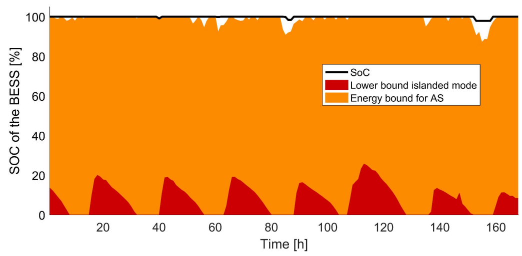

Figure 5: BESS SoC with FRRm up reserve provision

FRRm down reserves

In case of tertiary control down, two counteracting criteria have to be fulfilled. On the one hand, the BESS SoC should be kept as low as possible allowing to be recharged during a dispatch call for reserves provision. On the other hand, a minimum islanding energy requirement is demanded. Fig. 6 shows the compromise for the SoC that is made in order to fulfill both criteria.

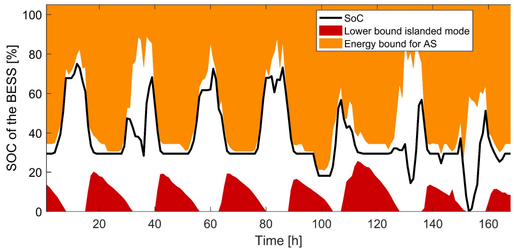

Figure 6: BESS SoC with FRRm down reserve provision

Bid sizes

The cost optimizing FC bid size for each product, battery capacity and season is summarized in Fig. 7. A larger BESS capacity generally translates into larger maximum bid sizes. For FCR, which is energy neutral on average, the energy storage capacity of the BESS is not limiting and much higher bids can be placed compared to the other products. Seasonal differences occur when the seasonally dependent minimum energy requirement for islanded operation (red area in Figs. 3 – 6) becomes a limiting factor. For the chosen BESS capacities, this is not the case for FCR and FRRm up, as they try to keep the BESS SoC at 75% and 100%, respectively anyway but it is for FRRa and FRRm down.

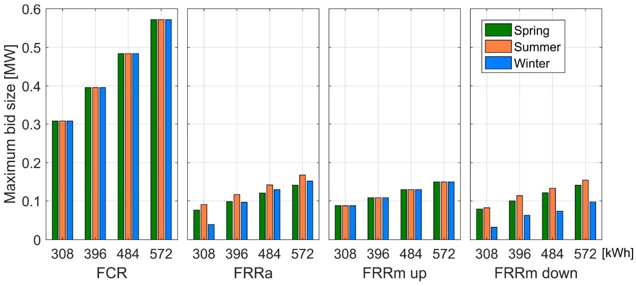

Figure 7: Resulting maximum FC bid sizes for each product, season and BESS capacity

Economic viability assessment

Providing FC has opposing influences on the financial balance of a MG. On the one hand, the MG is reimbursed for offering this service. On the other hand, reserving power and energy limits the flexibility of the BESS, which might decrease the level of consumption of self-generated energy and hence, increase the cost for importing electricity. Furthermore, costly PV curtailment was necessary to ensure the requested power and energy reserves in certain hours.
Using the maximum FC bid sizes for each product and season and assuming that the reimbursement for FC provision will remain on the same level as in the previous year, we calculated a yearly cash flow (revenues from control reserves, costs of PV curtailment, typical costs/revenues from a FRRa call, cost of battery losses) for the DSO. These are positive for all offered products compared to the base case. We then used these yearly cash flows and the initial investment costs for a BESS to compute the life cycle benefits depending on battery size and offered product. We assumed a total lifetime of 10 years, investment costs of 750 EUR/kWh and a discount factor of 3%. The results are summarized in Fig. 8. We identify that only the provision of FCR is clearly economically viable. For FRRm, the BESS investment costs exceed the revenue potential dramatically and revenues do not compensate for the initial investment costs. For FRRa, the calculated life cycle costs are close to zero and more in-depth analysis is required to give a definite statement about its rentability. For example, the costs for the SoC management (intraday trading) as well as for the load shifting were neglected in this analysis.

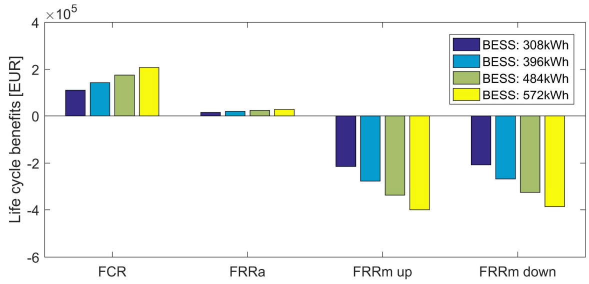

Figure 8: Life cycle benefits for each product

Fig. 7 indicates maximum bid sizes of similar order of magnitudes for FRRa and both FRRm products. The difference in the life cycle benefits, shown in Fig. 8 is mainly driven by the smaller reimbursement for FRRm.

CONCLUSIONS & OUTLOOK

The results show that FC provision with a MG featuring PV generation and a BESS is feasible and can serve as an income source for all products. However, by including a lifecycle analysis, we demonstrated that for all products except FCR, the financial burden of the initial investment outweighs the benefits given the assumed BESS costs.
Regarding the economic viability of providing FC with a MG in the future, one has to monitor price developments for BESS installation costs as well as the FC reimbursement. On the one hand, the investment costs for a BESS are likely to decrease in the future, but on the other hand, also the prices on the FC market might decrease as a consequence of increased supply by DERs employing FC business models.

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