ROBUST CONTROL STRATEGY FOR THE ENERGY STORAGE SYSTEM OF A MULTISERVICE DC MICROGRID

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ABSTRACT

The paper presents a lean control architecture for microgrids, with an implementation in direct current (DC) microgrids. The purpose of the developed solution is to combine local objectives (e.g., self-consumption of locally-produced energy) with system-level objectives (e.g., mitigation of power fluctuations).

INTRODUCTION

Due to the high variability and intermittent behavior of variable renewable energy sources (VRES), their integration in the distribution network can have a negative impact on its reliability. From an economic point of view, the stochastic behavior of VRES can reduce their benefit for prosumers, who may still have to exchange high levels of power and energy with the grid. It may also increase the cost of ancillary services for distribution system operators (DSO).

These problems are addressed here through the development of an innovative control strategy applied to a DC microgrid architecture. The drivers for a DC architecture are: i) increasing efficiency e.g., by eliminating multiple DC/AC conversions [1], ii) allowing an easier integration of DC VRES and iii) eliminating the need for synchronizing generators. Furthermore, the system reliability is improved with the reduction of complexity of the whole system [2]. DC micro-grids in buildings [3, 4] represent a technical solution to enhance the performance of power distribution at building and/or district level.

Building on prior theoretical work [5], we present here a practical implementation of this concept with an emphasis on providing multiple services with a storage system on the microgrid. We describe and characterize its control strategy and evaluate its economic merits based on storage costs and retail electricity prices.

SYSTEM ARCHITECTURE

The investigated system, depicted in Figure 1, is composed of:

- a bidirectional grid-tied inverter, establishing the interface between the DC microgrid and the upstream distribution grid;
- controllable and non-controllable loads supplied, if needed, though DC/DC converters;
- PV modules with dedicated power optimizers at module level;
- an energy storage system for energy and power buffering, directly connected to the DC bus.

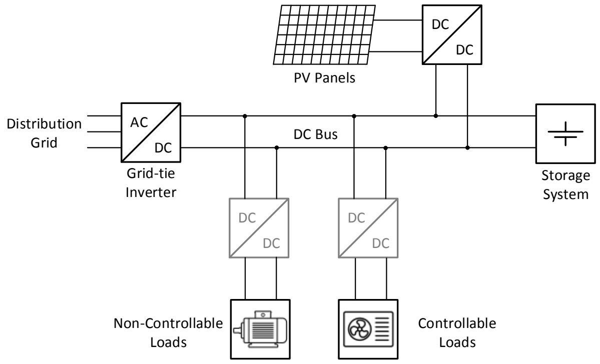

Figure 1: System architecture

The particularity of this design is the direct connection of the storage system to the DC bus whose voltage then varies depending on the state of charge (SoC) of the storage system. By knowing the link between voltage and SoC, it is thus possible to estimate the SoC through the measurement of the voltage. This approach is thus an extension of DC bus signaling [6], where the DC bus voltage carries the information on the current state of the system. It allows the implementation of a decentralized and scalable control strategy where each component connected to the DC bus has access to this information without a communication network.

The DC/DC converters supplying the loads are only necessary if the corresponding loads are not compatible with a variable supply voltage.

Finally, the loads are separated into two categories: the controllable and non-controllable ones. The first category gathers flexible loads with significant inertia (e.g., electric boiler, air conditioning) while the second gathers the remaining devices for which a shifting on their operating schedule is not possible without affecting the user. The controllable loads are supplied by a separated converter to be independently controllable.

CONTROL STRATEGY

Objectives

The purpose of the developed solution is to combine local and system-level objectives, namely:

1. increase self-consumption → reduction of energy cost for prosumers;
2. perform peak-shaving on the grid power → reduction in capacity charge for prosumers, reduction in peak load for DSO;
3. perform ramp-rate control of the grid power → reduction in rapid fluctuations for DSO.

General topology

The implementation of the control strategy is based on a multi-level approach. Its topology is split in three different levels (Figure 2): the physical system, the first control level characterized by fast and simple controllers, and the supervision level where more advanced and slower control techniques are used.

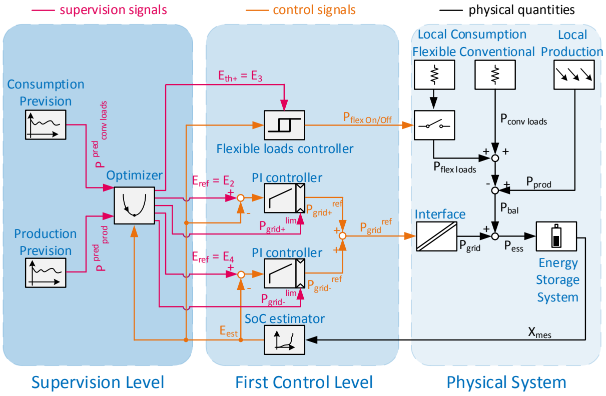

Figure 2: Detailed implementation of the control strategy

On the lowest level, the physical system includes all the devices presented in the previous section.
The first control level acts on two elements of the physical system: the grid-tied inverter and the controllable loads. The grid-tied inverter is controlled with two proportional-integral (PI) controllers and the flexible loads with a hysteresis comparator, both using the estimated SoC of the storage system.
The first decentralized control level can either be defined once and kept unchanged during the operation, or be dynamically optimized by a higher control layer, the supervision level. The purpose of this centralized control level is to improve the system performance by updating, at a slower rate, the first control level parameters.

Usage of PI controllers for the different services

The different energy services are provided through the use of the two PI controllers mentioned previously. Whenever these controllers lead to an imbalance between production (including grid imports) and consumption, the difference is handled by the local storage system.

Self-consumption

The increased self-consumption is achieved by unidirectional PI controllers with clearly separated reference values. One of the PI controller can only impose a grid power extraction while the other can only impose a grid power injection. The reference SoC value of the first PI controller is lower than the reference value of the second. Between these two reference values, no power is exchanged with the grid.

Peak-shaving

The same PI controllers are also used to perform peak-shaving on the grid power by setting saturation values to their output. This limitation is disabled before the SoC reaches the storage physical capacity.

Ramp-rate control

Finally, this service is also performed with the PI controllers, more precisely, through the definition of the closed-loop equivalent time constant [5]. The controller reacts with a limited and predefined bandwidth to a perturbation and therefore acts as a low-pass filter, effectively limiting the variations of the power exchanged with the grid.

Virtual splitting of the storage capacity

Each of these services is therefore related to specific ranges in the charge levels of the energy storage system. The storage capacity is divided by thresholds E_0-E_6 into three types of areas corresponding to the three energy services: blue for self-consumption and flexible load control, red for peak-shaving and yellow for ramp-rate control. This last area has to be considered as security margins against SoC overshoots due to perturbations on the power balance and the limited bandwidth of the PI controllers.

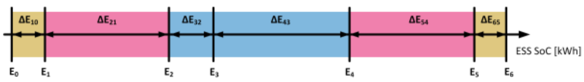

Figure 3: Distribution of the capacity of the energy storage system between self-consumption (blue), peak shaving (red) and ramp-rate control (yellow)

With this solution the relative weight of the services is flexible. A supervision level can therefore dynamically adapt this distribution in operations.

Temporal example

The control behavior is illustrated with a temporal example, in Figure 4, where the evolution of the different power flows and of the SoC is depicted.

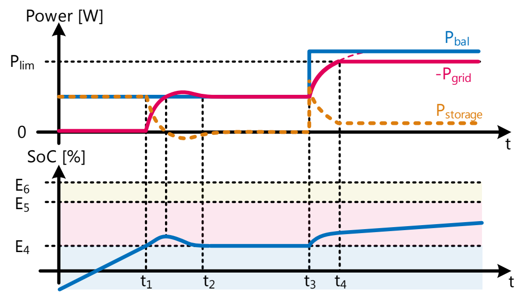

Figure 4: Temporal response of the control architecture to a varying power balance $P_{bal} = P_{production} - P_{consumption}$

- Before t_1, no power is fed back to the grid, the excess is stored in the storage system.
- At t_1, power is fed back to keep the SoC at that reference value.
- The SoC stabilized at t_2 after a transient caused by the controller limited bandwidth.
- At t_3, the power balance increases and exceeds P_{lim}. The grid power tries to follow this perturbation until reaching the limitation at t_4.
- After t_4, the grid power is saturated and the excess of production is stored → SoC increases.

SIMULATION RESULTS

The control strategy behavior was first validated in simulation. Figure 5 illustrates the performance of the control strategy for the ramp-rate control and peak shaving.

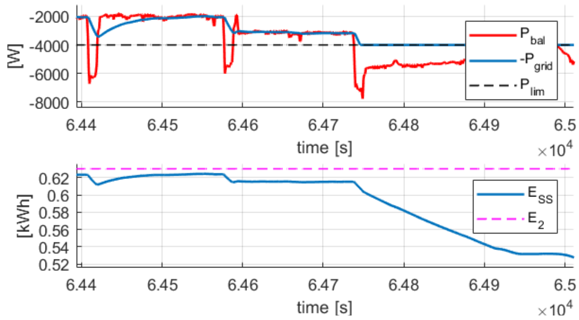

Figure 5: Illustration of the peak shaving (to 4 kW) and ramp rate control in response to a highly fluctuating balance between production and consumption: power flows in the system (top), state of charge of the storage system (bottom)

This figure shows that the grid power follows the power balance with a limited bandwidth, trying to keep E_{SS} at the reference thresholds E_2. When the power balance exceeds the power limitation, the extracted grid power is correctly limited. The missing power is supplied by the storage system which results in a decreasing E_{SS}.

ECONOMIC ASSESSMENT

The economic potential of the system was evaluated based on two parameters: electricity prices (both energy and power components) and levelized cost of storage.

Case study definition

The analysis was performed on a one-year simulation with a domestic load profile representing a yearly consumption of 5.4 MWh. A high-resolution irradiance profile [7] was used to compute the generation profiles. The storage system was assumed non-ideal with a 90% round-trip efficiency.

The yearly operating cost was computed depending on the installed storage capacity and the PV sizing ratio (i.e, annual PV production / annual consumption). The control parameters (i.e., thresholds and power limitations) were optimized to minimize the yearly operating cost.

The economical assessment was made in comparison with a basic storage control strategy which stores excess production until the storage system is full and complements production shortage until it is empty.

Impact of electricity prices

The effect of the prices on the solution profitability was studied to evaluate the influence of energy-based vs. power-based pricing. The assessment uses the billing rates applied by the DSO and energy provider of the city of Neuchâtel for a low-voltage grid connection which charges the energy as well as the maximum power drawn from the grid.

In particular, two different tariffs, B2A and B2B, are compared. The first one puts more weight on the energy cost (~4 CHF/kW/month, ~18 cts/kWh) and the second one on the power cost (~14 CHF/kW/month, ~14 cts/kWh). The feed-in retribution is the same for both tariffs (~12 cts/kWh).

Figure 6 presents the yearly difference in operating cost, in CHF, between a basic storage system and the developed solution, for both tariffs, as a function of the PV sizing ratio and the storage capacity.

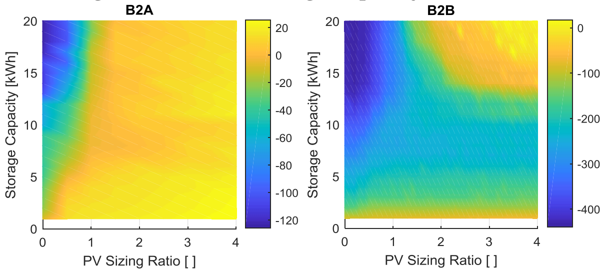

Figure 6: Difference in annual operating cost with a basic storage system for an energy-heavy tariff (left) and for a power-heavy tariff (right)

These results first show that the economic performance of the developed system is highly linked to the applied tariff, especially the cost of power. For an energy-heavy tariff, the two systems are equivalent for a PV sizing ratio higher than 1.5. In that situation, performing peak-shaving is not profitable as the cost of power is not significant enough. Therefore, the whole storage capacity is used for self-consumption. This kind of tariff obviously reduces the economical appeal of our technology compared to a basic one.

On the opposite, a tariff that emphases the cost of power leads to significant savings with our system. As an example, for a realistic setup with a storage capacity of 8 kWh and a PV sizing ratio of 2.5, our system brings annual savings of 240 CHF (16%) compared to a basic storage system. This is mainly linked to the peak shaving which allows significant savings on the power-related costs. In that case, the potential of multiple services provided by the developed solution is fully exploited. Such a system is therefore particularly appealing for applications characterized by important peaks in power consumption.

Impact of LCOS

The levelized cost of storage (LCOS), in CHF per kWh stored, accounts for the initial cost of the storage system and its lifespan. For this assessment, the following setup was evaluated: installed storage capacity of 8 kWh, PV sizing ratio of 2.5 and power-heavy tariff B2B.

The analysis was made for an LCOS varying from 0.05 CHF/kWh to 0.25 CHF/kWh, which represents a realistic range for current and upcoming LCOS. Indeed, Lazard estimates the LCOS of microgrid lithium-ion batteries (excluding electricity price and taxes) between US$ 0.21/kWh and US$ 0.23/kWh in 2017 and expects a 36% decline in capital costs in five years [8].

Table 1 summarizes the relative savings achieved by the developed solution and a basic storage compared to a system without storage as a function of the LCOS.

Table 1: Effect of LCOS on the savings brought by an energy and power buffering system

LCOS [CHF/kWh]	Savings with basic storage [%]	Savings with our solution [%]
0	5.2	20.0
0.05	-3.6	13.3
0.10	-12.4	6.4
0.15	-21.1	2.7
0.20	-29.9	-2.1
0.25	-38.7	-7.6

The first observation which can be made is the poor profitability of a basic storage system, which only brings savings for an LCOS below 5 cts/kWh. Indeed, if the LCOS is higher than the difference between import and export prices, it is less expensive to feed an excess of production back to the grid than to store it locally for later consumption. In other words, it is not profitable, with current levels of feed-in tariffs, to use a storage system to increase self-consumption only.

However, the developed solution becomes already profitable for an LCOS of 15 cts/kWh i.e., more than 10 cts/kWh before a basic storage system. It is able to achieve such performance by providing multiple services. Although this system is not profitable with current storage costs, it is expected to become profitable sooner and in a greater extent than a basic control strategy. Beyond that, remunerating the service of ramp-rate control could further increase the system profitability. Indeed, future billing policies are predicted to value more this aspect [9].

DEMONSTRATOR

Besides theoretical assessment, an industrial-size demonstrator (Figure 7) was developed to experimentally validate the theoretical observations. This 20 kW demonstrator is being installed in an industrial environment to supply motor drives. This demonstrator will be connected to a 10 kW_p PV installation and to a 1 kWh storage system.

Figure 7: Control and conversion cabinet of the demonstrator

CONCLUSION

Achievements

DC micro-grids represent a valid alternative to increase the penetration of VRES without affecting the power quality in the public AC distribution systems.

An innovative control strategy with multi-objective capability is presented. The high flexibility of the developed solution allows dynamic optimization of its control parameters to maximize its profitability. The proposed control strategy is validated in simulation, from a technical and economic point of view. The economic assessment has shown a clear potential for effective savings.

Future work

We intend to improve the simple, flexible load controller with more grid-interactive control features such as demand response. Future work also includes the implementation and assessment of the supervision level. Finally, experimental validation is planned once the demonstrator is operational, in the fourth quarter of 2018.

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