Performance of combined renewable generation and storage in the context of energy firming

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ABSTRACT

This paper analyzes the performance of hybrid power generation combining renewable sources with battery energy storage systems in the context of grid codes that require a preannouncement of the generated power. The produced energy is remunerated with a fixed price; in the case that there are deviations from the announced schedule, penalties have to be paid. This leads to a scheduling optimization problem that makes a trade-off between these two risks based on statistics of the renewable power forecast accuracy. The main contribution of the paper is the analysis of the revenue performance ratio and its dependency on the accuracy of the forecast. The results show that there is optimization potential for maximizing the revenue by intelligently designing the energy commitment and the control. Further on, even for large errors of the forecast, the losses and the penalties are limited, so the financial risks with respect to the generation forecast are low.

INTRODUCTION

Distributed generation plays an important role in the future power systems, already now getting a more and more significant proportion of the total generation. In order to provide stability for future power systems, the grid connection regulations are recently imposing that the distributed generation is predictable, e.g. provide a schedule of the generated power. This is difficult to be achieved by the renewable generation sources due to the intrinsic volatility of the primary energy source and consequently they need to be combined with energy storage systems.

The topic of this paper is the analysis of the performance of hybrid power generation with renewable generation combined with battery energy storage systems (BESS) in the context of grid codes that require a pre-announcement of the generated power, for example the French grid code (CRE) for grids outside the European interconnected grid [1]. The analysis is general also for other similar contexts, like day-ahead energy contracting and intraday compensation in case of deviations.

The paper addressed the following aspects: scheduling optimization and control of the microgrid including the analysis of the grid code requirements, analysis of the renewable generation forecast accuracy and finally the analysis of the plant performance dependency on the forecast errors.

PROBLEM FORMULATION

The system model is illustrated in Figure 1. On the electrical part, it comprises of renewable generation sources (typically photovoltaic and/or wind power), energy storage systems, power conversion and grid connection components. On the control side, the Energy Management System (EMS) is using a Weather Forecast to predict the renewable generation and then it optimizes the power schedule for the next day considering the plant capability (e.g. storage size) and the tradeoff between remuneration for the sold energy and penalties in the case of deviations from the schedule as well as aging of the components (mainly the storage). The scheduling can be mathematically formulated as a dynamic optimization problem, the time dependency being given by the storage and by grid code constraints regarding the maximum change rate of the output power. The time resolution is high, e.g. in the CRE grid code the schedule resolution is 1 minute. During the power production, the schedule is fixed, but the EMS still has the potential to optimize the control in case that the reality does not match the forecast.

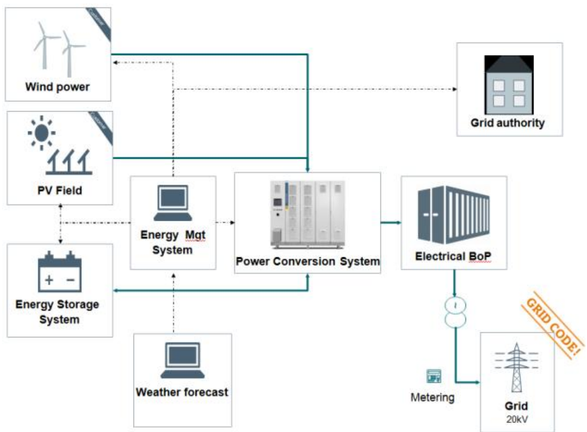

Figure 1. Block diagram of the microgrid

The CRE grid code requires a day-ahead announcement of the produced power and allows a number of 3 re-announcements at fixed times over the day. The re-announcements during the day have to specify updated values for the interval beginning 2 hours after the re-announcements and ending at 24:00. The value for the first minute has to be identical to the value specified in the previous announcement for the same minute.
The scheduled power has a maximum value of 70% of the nominal peak power of the plant. We denote the peak power of the plant P_0. Further on, the variation of

the power during the scheduling is constrained between -0.6%*P_0 and +0.6%*P_0, depending on the time of the day. Details can be found in [1].

The produced energy is remunerated at a fixed price agreed between the plant operator and CRE during the project bidding. In case that there are deviations between the announced power and the produced one, the plant operator has to pay penalties. There is a grace interval around the announced power, P_{ref}, of 5% * P_0 in which no penalties are paid. In case of underproduction, i.e. the produced power P_{prod} is below the scheduled value P_{ref} by more than 5% P_0, then the penalty is

$$Penalty = (P_{\mathrm{ref}}\text{-}0.05*P_0 - P_{\mathrm{prod}}) * (P_{\mathrm{ref}}\text{-}0.05*P_0 - P_{\mathrm{prod}} + 0.2*P_0) * Price/60/P_0.$$

This formula means that the Penalty is 0 if $P_{prod} = P_{ref}$-0.05 and it is increasing quadratic with the amount of under-production.

In case of overproduction, the penalty is equal with the remuneration, so the revenue becomes zero. This case can be easily avoided, because generally the energy production can be curtailed easily and the injected power in the grid reduced.

The grid code requires the installation of a battery energy storage system (BESS) and gives a minimum size for it: the power capability of the BESS has to be at least $P_0/2$ and the usable capacity has to be at least $P_0/2$*1hour. The usable capacity is to be demonstrated yearly, this requirement determining the lifetime of the BESS.

Power announcement optimization

The day-ahead power announcement is optimizing the expected revenue of the plant which is given by the following expression:

$$Revenue = E_{\mathrm{Prod}} * Price - Penalties$$

where:

$E_{\mathrm{Prod}} = \Sigma\, P_{\mathrm{Prod}} * \Delta t$ is the produces energy as sum of the injected power in the grid, evaluated using a sampling interval Δt, Δt = 1 minute,

Price – price of the unit of energy, agreed with the grid regulatory body,

Penalties – penalties to be paid in case there are differences between the scheduled energy and the produced one, again integrated over the day.

The optimization has to take into the trade off between remunerated energy and the penalties. Especially the severity of the penalties is of high importance: in case these are very high, the scheduler has to be more conservative, while if these are small, the scheduler has to me more aggressive. In figure 2 we have depicted the revenue dependency on the difference between the

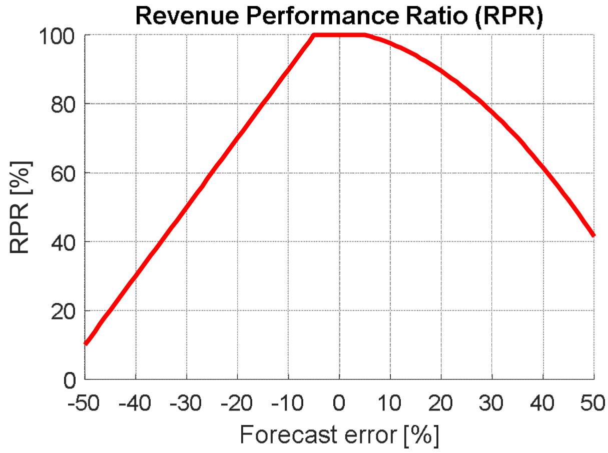

Figure 2. Dependency of the RPR to the scheduling error

scheduled and the produced power. Negative error due to a too conservative scheduling results in performance reduction due to curtailment of the renewable power. Notice that this loss is linear with the error between the scheduling and the true available power. Positive error due to a too aggressive scheduling results in performance reduction due to penalties. The penalties are quadratic in the scheduling error, but actually not very high and consequently a more aggressive scheduling is beneficial.

The Revenue Performance Ratio (RPR) is defined as the ratio between the actual revenue and the maximum revenue given by the available renewable generation without curtailment.

$$RPR = Revenue\,/\,(E_{\mathrm{Renewable}} * Price)$$

The power announcement is formulated as an optimization problem to maximize the expected revenue:

$$\underset{\mathrm{Pref}}{\operatorname{argmax}}\, Revenue,$$

given the constraints enumerated before and taking into account the accuracy of the day ahead forecast of the renewable production.

In [3], the authors describe a stochastic approach to solve this optimization. In the results presented in this document, we have used an approximate simplified method, fixing the announcement to be proportional to the power forecast. Consequently, we have defined a “trust factor” of the power forecast that scales the forecast up or down. This factor has been optimized dependent on the trade off between penalties and curtailed energy and the expected forecast accuracy.

BESS modelling and sizing

The BESS is modelled with a quasi-stationary model with a time resolution of one minute, appropriate for the setup of the analysis. The model considers the electrical and thermal short term effects and delivers the limitations of the capability (capacity and power) of the BESS. Further on, the calendaric and cyclic aging is modelled, to achieve an accurate modelling of the BESS lifetime [4].

The BESS lifetime plays an important role in the economical optimization of the plant. In our investigation we have considered the BESS lifetime as a constraint for the optimization. Concretely, the BESS size was designed so that lifetime is at least 10 years, i.e. after 10 years remaining usable capacity is at least $P_0/2$*1h, as requested by the grid code.

RENEWABLE GENERATION FORECAST

One of the main aspects for the performance evaluation is the modeling of the uncertainties in the system. The weather and its forecast play here the major role. It must be made the differentiation between multi-annual irradiance expectation, which influences directly the total amount of renewable generation, and the short term (day ahead and below) forecast relevant for the scheduling and control process. This paper focuses on short term forecast influence on the scheduling and the sensitivity of the performance on its accuracy.

There are several metrics for the evaluation of the performance of the forecast accuracy, a good overview can be found in [2]. For the energy firming with the day ahead scheduling use case, the most important metric is the daily mean bias error normalized to the typical daily plant production, i.e. the sum forecast error over the period of a day. This measure is an indication of the energy that the BESS has to compensate in the case of a wrong forecast. An example of such a distribution obtained from a back-test performed over the duration of 3 years it is presented in Figure 3. It is relevant to observe that the forecast has a low mean error (the distribution is centered on zero), but it has quite a large spread requiring a large BESS size to avoid penalties.

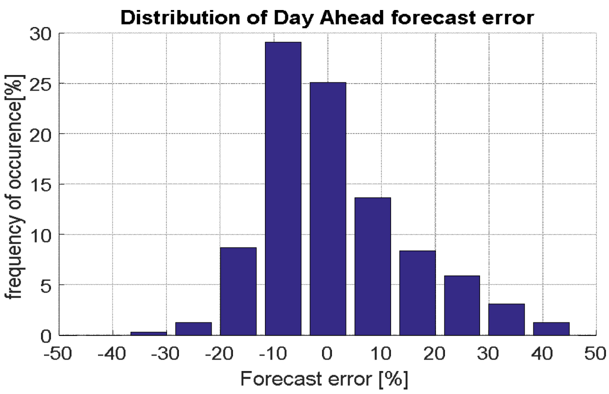

Figure 3. Distribution of the day ahead generation forecast error

SYSTEM RESULTS

In Figure 4 we present the operation of the system for an exemplary day. It can be observed that the available PV power at the panels (blue curve) is fluctuating strongly, due to clouds covering the sun. The forecast (green curve) is matching fairly well in average the production, but it cannot predict accurately the power dip-ins. The power announcement (red curve) is according to the requirements of the grid code with respect to ramp rates and maximum power, being slightly lower than the forecast.

Given the announcement, the EMS is controlling the grid infeed (magenta curve) to respect the power schedule. The degrees of freedom for the controller are the use of the BESS and also the 5% band around the announcement, in which no penalties have to be paid. This band is used at its maximum extent to shape the state of charge (SOC) of the BESS, to avoid penalties and also to avoid energy waste when the schedule is less than the available power.

Notice that due to the good match of the forecast for this day, the revenue is equal with the available power, i.e. the schedule can be followed and no penalties has to be paid, and also the entire available PV power is feed into the grid and remunerated. This must not always be the case: in the analysis of the forecast accuracy (Figure 3), it can be observed that there are also days with large forecast errors, both in the positive and in the negative range. Even for a quite large BESS size these errors will produce losses due to penalties and due curtailment of PV power that cannot be fed to the grid and also not stored in the BESS because it is full.

The revenue performance ratio (RPR) is shown in Figure 5. The expected RPR of the plant is obtained for the distribution of the day-ahead forecast error determined from the back-test experiment. This case is shown in Figure 5 for a systematic error of -3% and is equal with 84.3%. The RPR is less than 100%: even with the compensation possibilities given by the battery storage system and the optimization approach, there will be grid infringements for days where the forecast matches poorly the reality. Also there will be energy curtailment, when the forecast is significantly lower than the true power of the day. It is interesting to remark, that for the back-test data, the optimized solution results in losses due to penalties approximately equal with the losses due to energy curtailment.

One of the main contributions of the paper is the analysis of the sensitivity of the performance with respect to the bias of the above distribution, i.e. a systematic error in the forecast. This is the major factor influencing the performance. The analysis was performed by systematically shifting the data toward optimistic and toward pessimistic forecast. The influence on the performance is shown in Figure 5.

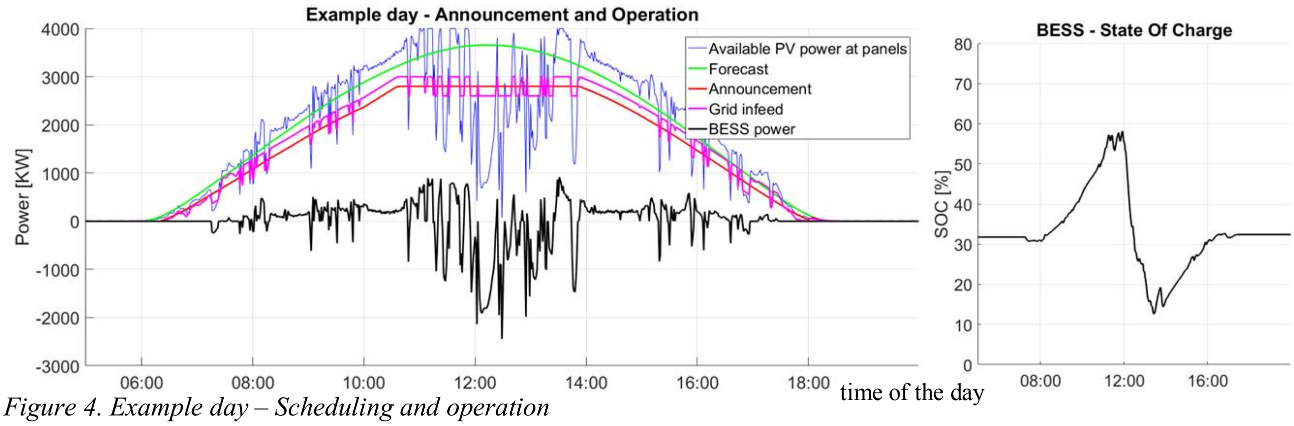

Figure 4. Example day – Scheduling and operation

It can be observed that in case of pessimistic forecast (negative systematic error) the losses in the sold energy (Energy to grid, E2G) increases and the losses due to penalties decreases, while in case of optimistic forecast (positive systematic error) the balance is the other way around.

Nevertheless, the variation range of the RPR is not very large and comparable with losses due to other effects like thermal losses in the equipment. Consequently, it can be stated that the revenue is quite robust against forecast mismatches.

CONCLUSIONS

In this paper we have made an analysis of the performance of a combined photovoltaic and battery storage system plant in the context of energy firming in the French grid code (CRE) for grids outside the European interconnected grid. We have shown that the optimization of the energy commitment is dependent on the tradeoff between paying penalties and energy curtailment. We have analyzed the expected weather forecast accuracy and made an analysis of its influence on the revenue performance.

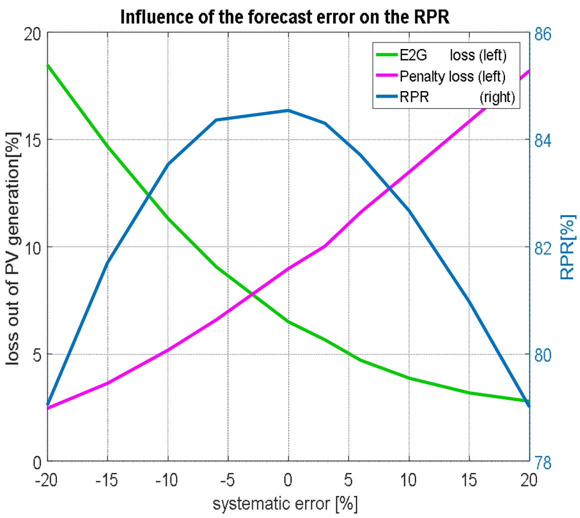

Figure 5. Dependency of the plant performance depending on the systematic errors of the forecast

The results show that there is optimization potential for maximizing the revenue by intelligently designing the energy commitment and the control, so the design of the plant has to be carefully planned. Further on, even for large errors of the forecast, the losses and the penalties are limited, so the financial risks are low, if the other aspects of the plant design are considered properly.

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