TECHNICAL IMPACTS ON DISTRIBUTION SYSTEMS OF MEDIUM-SIZED STORAGE PLANTS PARTICIPATING IN ENERGY AND POWER RESERVE MARKETS

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ABSTRACT

The increased contribution of renewable production into the generation mix is leading to a growing need of flexibility in electrical systems that can be partly provided by storage units. These stations are characterized by an important flexibility but are subject to operational restrictions due to their limited capacity. Currently, their added value is therefore derived when they are included within an existing portfolio. Storage utilities are consequently mainly participating in power markets related to the transmission grid, even when they are installed at the medium-voltage level. In this context, this work aims at quantifying their impact on the operating conditions of the distribution network. More particularly, the investigated case study illustrates that such storage plants may have a significant negative impact on the distribution network operation.

INTRODUCTION

The large scale introduction of distributed renewable generation, which is highly variable and with a limited predictability even in the short-term, has consequences that are difficult to manage for both transmission and distribution system operators.

However, contrary to the transmission systems that are equipped with metering devices and state estimation tools for identifying in real time or even anticipating the potential problems as well as different mechanisms to quickly solve such issues, the distribution network are not equipped with such technologies. Specifically, the temporal discrepancy between generation and consumption in specific locations of the network may result in voltage and congestion issues during some critical periods (e.g. in case of low demand combined with high distributed generation).

Overall, there is a great need of flexibility in power systems and it is indispensable to find solutions less expensive than reinforcing the network. In this way, the energy infrastructure as well as the customer behaviour must change and new perspectives have to be considered.

Currently, two solutions are mainly investigated. The first one is to move towards more active networks, whose principle is to adapt consumption patterns to available generation. This implies increasing the involvement of the end-users in the network operation by implementing demand-side management techniques such as Time of Use tariffs or by investing in smart appliances able to be controlled by an external operator. A second examined solution is the storage of electricity.

Nevertheless, in distribution systems, the issues are essentially local and big centralized storage utilities designed for maintaining the system frequency are thus not relevant. Likewise, a storage device located at the end-user level is not profitable for regulation policies that do not encourage self-consumption with appropriate incentive mechanisms due to current price and efficiency of available technologies. Therefore, an appropriate option lies between those two solutions through a flexibility unit of a power up to a few MW allowing the mutualisation of the needs of several customers.

In this context, the use of former quarrying sites, mines or natural slopes for pump hydro storage, which allows bypassing onerous installation costs by taking advantage of existing potential in regions with an industrial legacy, constitutes an attractive option. Such a solution is thus investigated in the Walloon Region that disposes of several sites that could accommodate utilities with a power up to a few MW that can operate at their maximum output power during 4 to 6 hours.

However, contrary to the transmission level that offers a sustainable environment for guaranteeing the grid safe operation, distribution level is not yet designed to address the challenges progressively emerging in an already ageing network. In this way, although there is a growing need to implement an adequate ancillary services market at the distribution level in order to solve local issues, such an environment is slow to materialize.

The profitability of flexible plants has thus to be ensured otherwise. Currently, these units offer a real added value when they are included within an existing portfolio. Indeed, mixing several technologies allows to optimally combine the technical specificities of different units (e.g. using flexible thermal power plants and storage stations to wipe out prediction errors of renewable generation) while reducing the dependence between their generated energy. This offers the benefit of mitigating both the uncertainties related to global prediction error as well as the risk due to contingencies such as the loss of a generating unit, which consequently leads to decrease the volatility of the expected profit over time.

Consequently, storage plants are mainly participating in power markets related to the transmission grid, even when they are installed at the medium-voltage level. Their actions are nonetheless affecting the operating conditions of the distribution network and it is important to quantify these contributions. Practically, this work

aims at evaluating the technical impacts in the neighborhood of pumped-storage hydroelectricity plants (PSHs) pertaining to a larger portfolio participating to energy and power reserve markets.
More particularly, this work focuses on voltage levels, line power flows and their associated losses within distribution grids in which PSHs are connected. The paper is organized as follows. The determination of the optimal operation of storage plants is described in Section II. Then, the methodology for assessing the impact of the scheduled operation is explained in Section III and tested in Section IV for a PSH of 5 MW – 25 MWh installed on a radial network supplying an industrial estate encompassing 24 industrial companies located in Belgium. Finally, relevant conclusions and perspectives are presented in Section V.

OPTIMAL OPERATION OF STORAGE PLANTS

Storage units offer a real added value when they are included within an existing portfolio due to the current regulation policy as well as their limited energy capacity preventing them to guarantee providing power during a long period of time [1]. Here, two-stage stochastic programming is used as a modelling framework for the short-term management of the considered portfolio. Such a technique aims at maximizing the expected value of the profit on a defined period (typically one day). In the first stage, facing future uncertainties, the portfolio manager has to decide on the optimal bidding strategy to adopt in the power markets as well as the unit commitment of its generation utilities. It represents day-ahead decisions that cannot be modified in the future when the uncertainty set is resolved. The second stage of the model corresponds to hour-ahead operation of the flexible plants (i.e., thermal units and hydro plants with storage) that aim at avoiding portfolio imbalances while providing the power requested for ancillary services towards the system operator. The second-stage decisions depend on the realization of the stochastic parameters of the problem. In this work, the considered uncertainties are the load and renewable generation within the studied portfolio as well as electricity prices. The problem can be formulated as a mixed-integer linear program (MILP) as follows:

$$\max_{\mathbf{x},\mathbf{y}} \mathbb{E}(\Phi) \quad (1)$$

$$\mathbb{E}(\Phi)=\sum_{\omega\in\Omega}\sum_{\tau\in \mathrm{T}}\pi_{\omega}\begin{Bmatrix}\Phi^{\text{DAM}}_{\omega,\tau}(\mathbf{x})+\Phi^{\text{IM}}_{\omega,\tau}(\mathbf{y})+\Phi^{\text{AR}}_{\omega,\tau}(\mathbf{y})\\ -\text{ImbPen}_{\omega,\tau}(\mathbf{y})-\text{Pen}^{AR}_{\omega,\tau}(\mathbf{y})\\ -\sum_{\upsilon\in\Upsilon}\left\{c^{\text{op}}_{\upsilon,\omega,\tau}(\mathbf{x},\mathbf{y})+c^{\text{var}}_{\upsilon,\omega,\tau}(\mathbf{y})\right\}\end{Bmatrix}+\beta.\text{Risk} \quad (2)$$

$$\mathbf{x}_{\min}\le\mathbf{x}\le\mathbf{x}_{\max},\ \mathbf{y}_{\min}\le\mathbf{y}\le\mathbf{y}_{\max} \quad (3)$$

$$f_{\upsilon}(\mathbf{x},\mathbf{y})\ge 0 \quad (4)$$

$$f_{\upsilon}(\mathbf{x},\mathbf{y})=0 \quad (5)$$

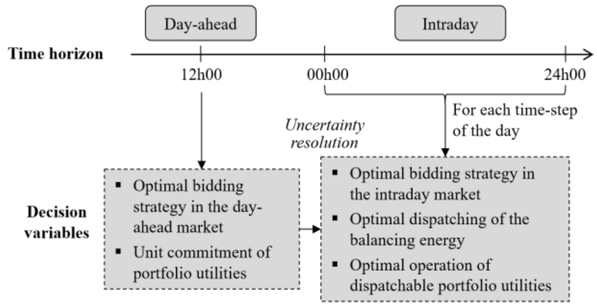

Figure 1 - *Short-term decision schedule of the portfolio.*

where Ω is the set of all stochastic scenarios and π_{ω} their associated probabilities, T the set of all time steps and Υ the set of all portfolio units.
The first three terms of the objective function (2) stand respectively for the profit realized in day-ahead $\Phi^{\text{DAM}}_{\omega,\tau}$ and intraday $\Phi^{\text{IM}}_{\omega,\tau}$ markets as well as the profit for the actual activation of the ancillary services $\Phi^{\text{AR}}_{\omega,\tau}$. Then, the terms representing the financial penalties faced in case of energy imbalances $\text{ImbPen}_{\omega,\tau}$ and non-activation of the power reserves $\text{Pen}^{\text{AR}}_{\omega,\tau}$ are included. The last contributions $c^{\text{op}}_{\upsilon,\omega,\tau}$ and $c^{\text{var}}_{\upsilon,\omega,\tau}$ refer to expenses associated respectively with the operation of generation and storage units (i.e. running, start-up and shut-down costs) as well as with grid fees and taxes.
The traditional formulation of two-stage stochastic programming is risk-neutral. However, in presence of variability, it may be useful to adapt its policy according to its tolerance for risk. For this reason, the conditional value-at-risk (CVaR) is introduced into the formulation. The CVaR allows taking more conservative solutions in order to be more robust towards extreme scenarios, but at the expense of the profit generated for more likely situations. Moreover, it can be expressed by means of linear expressions and offer the opportunity to choose among different risk levels by adjusting the β parameter [2].
The operating range of decision variables are defined in (3). The constraints in (4) and (5) reflect the technical requirements and initial operating conditions specific to each unit. This work is mainly based on [3] in order to reduce the number of binary decision variables. Concerning conventional power plants and storage utilities, the constraints include the ramping limits, the minimum up and down times and the adjustment of output power due to their participation in ancillary services. For storage units, the evolution of state-of-charge has also to be considered. Finally, the energy balance equation and the non-anticipativity constraints that enforce first-stage decision variables to agree across scenarios are modelled.

MONTE CARLO ENVIRONMENT

The Monte Carlo simulation is a mathematical technique that allows accounting for the random behavior of some variables within the studied system. In our case, the stochastic variables are the consumption and the generation of each customer of the studied grid during the day. Here, a sequential Monte Carlo environment is implemented whose general structure is represented in Figure 2. The developed process simulates thus, for each experiment, the random behavior of the different customers by the means of typical load profiles [4]. The wind power generation, however, is modelled using ARMA time series.

The principle is to generate a large number of system states in order to provide time-varying consumption and generation patterns that are statistically representative of the actual behaviour of all customers. Specifically, daily profiles are sequentially generated along with the optimal operation of the storage plant included in a generation portfolio. These profile allow therefore to accurately determine the system state and to obtain numerical outcomes (e.g. probability of overvoltage at each node of the system). Indeed, a balanced load-flow algorithm computes the voltage profile along the different feeders of the network as well as line power flows considering the sampled energy flow values at each node and the sampled voltage at the head of the feeder. The procedure is repeated numerous times in order to test a large amount of possible combinations. For obtaining a good convergence threshold (< 0.1%) on the results, it is shown that 10,000 simulations is a good trade-off to keep acceptable computation times [5]. The total impact of the storage station on the system operation is then computed by averaging the global effects provided by all Monte Carlo iterations.

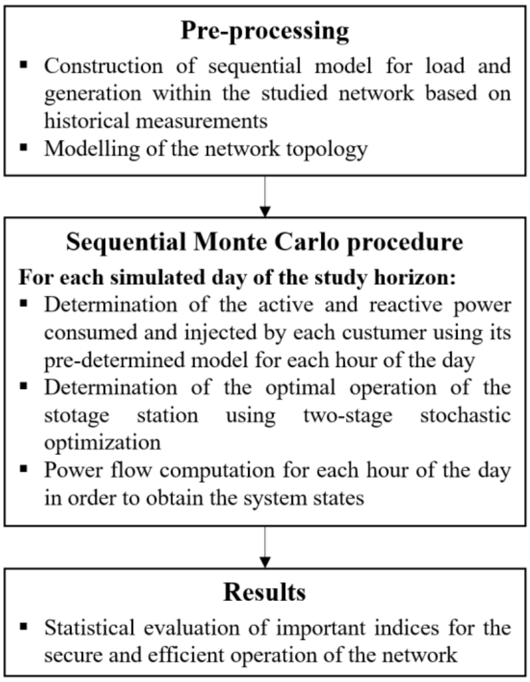

Figure 2 - *Flowchart of the general principle of the long-term analysis tool.*

CASE STUDY

The methodology is tested on a radial 10 kV distribution network, represented in Figure 3, supplying an industrial estate encompassing 24 industrial companies located in Belgium. The nodes 22, 23, 29 and 30 are strategic nodes ensuring an interconnection with the rest of the MV network in the event of technical incident such as short circuit or transformer failure.

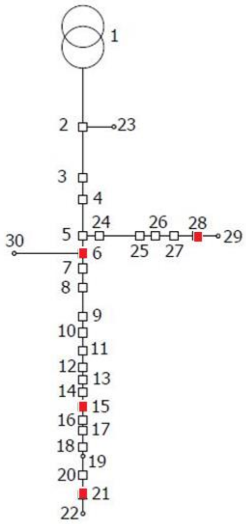

Figure 3 - *Representation of the 10 kV network.*

This network has recently become critical as regards the risks of congestion and voltage violation because of the progressive integration of DG units such as wind farms or large PV plants. These are installed at nodes 6, 15, 21 and 28. This situation is indeed stimulated by the current financial attractiveness of investing in renewable energies.

The influence of a medium-sized storage station (5 MW – 25 MWh) on this grid operation is studied. It should be noted that, contrary to other storage technologies, the localization of PSH is imposed by the topographical constraints, and may therefore be either highly or weakly influential. The importance of this factor is here studied through a sensitivity analysis on the unit positioning.

The PSH unit is included in a classic portfolio constituted of 2 conventional power plants (CPPs), 2 pump-storage hydroelectricity plants (PSHs), 5 wind parks for a total installed power of 120 MW as well as 10.000 residential clients among which 20 % are equipped with rooftop photovoltaic (PV) installation, typically between 3 and 5 kVA. In this way, the operation of the PSH is defined by the whole portfolio strategy for optimizing its profit.

The objective of this work is to firstly statistically evaluate the impacts of this operation on the voltage level (Figure 2). Thanks to the probabilistic simulation, the overvoltage risk can be defined for each node during the studied period. Such voltage violations are defined in accordance with the European EN50160 standard [6], i.e. the voltage cannot vary more than 10 % around its nominal value.

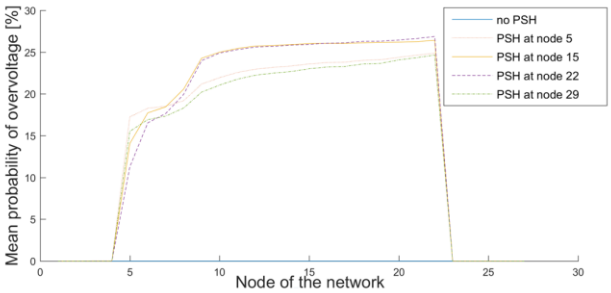

Figure 4 – *Probability of overvoltage for the different investigated configurations.*

Table 1 gives the probabilities (over the whole year) of voltage violations as well as the total actives losses within the studied system. These losses are computed as follows:

$$P_{loss} = \sum_{i=1}^{L} R_i I_i^2 \tag{6}$$

where R_i and I_i correspond respectively to the resistance and the current flowing in each of the L lines.

Table 1 – *Summary table of the results.*

Scenarios	Average voltage violation [%]	Average hourly losses [kWh]
Without storage	1.26	309.58
Storage at node 5	14.87	413.58
Storage at node 15	16.01	490.73
Storage at node 22	15.82	561.03
Storage at node 29	1.41	309.92

From Figure 4 and Table I, it arises that PSH units may have a significant negative impact on distribution systems when it is operated with non-local purposes. Such results can be explained with a deeper analysis of the storage station use. Indeed, as expected, the unit is discharging when electricity prices are high, i.e. when the total demand at the country level is important and the generation capacity limited. Hence, if the local situation within the distribution grid is not similar, the actions of the storage can go against local interests. In this way, it can be concluded that the impact of the PSH unit on the network operation strongly depends on situation within the whole system.

CONCLUSIONS AND PERSPECTIVES

This paper is devoted to the study of local technical impacts of storage plants installed at the distribution level but operated for solving issues related to transmission systems.

The influence of the station mainly depends on two considerations, namely its position in the network as well as the correlation between consumption on the studied network and total load within the whole system. For the studied application, it has been shown that the storage unit may even deteriorate the local situation.

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