CURTAILMENT OF DISTRIBUTION-SIDE POWER GENERATION FOR PRIMARY SUBSTATION INVESTMENT DEFERRAL

Aurel GARRY(*)
Univ. Grenoble Alpes, G2Elab,
F-38000 Grenoble, France
aurel.garry@g2elab.grenoble-inp.fr

Florent CADOU(*)
Fondation Partenariale de Grenoble INP
florent.cadoux@g2elab.grenoble-inp.fr

Marie-Cécile ALVAREZ
Univ. Grenoble Alpes, G2Elab,
F-38000 Grenoble, France
marie-cecile.alvarez@g2elab.grenoble-inp.fr

Nouredine HADJSAID
Univ. Grenoble Alpes, G2Elab,
F-38000 Grenoble, France
Nouredine.Hadjsaid@g2elab.grenoble-inp.fr

Antoine MINAUD
ERDF – France
antoine.minaud@erdf.fr

ABSTRACT

This article deals with a methodology to set the compromise between substation investment and distribution-side power generation curtailment, in situations where the rated power of the substation is sized by power exports. An algorithm was developed as a decision tool, based on a stochastic approach, in order to minimize the total cost, which reduces it compared to a reinforcement strategy and reduces the cost dispersion of a decision based on a deterministic planning.

INTRODUCTION

The planning of medium voltage distribution grid is a complex problem, in particular due to large scale and long timescales, which implies huge uncertainties. Many models were proposed in the literature with regards to planning methods under uncertainties which is usually a very large problem [1]. Its scale may be reduced by fixing uncertain parameters, for example with measurements data. It allows focusing on specific issues, such as comparing the efficiency of classical versus smart grids solutions on a given problem [2], or developing grid planning methodology [3].

Most substations are currently sized to handle the future “plausible” peak demand, that is to say, the probability that the substation will be overloaded in the future should be lower than a given risk threshold. When the probability of exceeding the substation rated power is becoming too high, a substation investment, or any other option to relieve the constrained part of the grid, is required.

When the substation investment is driven by distribution-side power generation, without risk of outreaching the limit during times of high consumption, the situation is quite specific. Indeed, critical power flows in the substation correspond to times of simultaneous high generation and low consumption; but the statistical behavior of most decentralized power generating sources is such that times of highest (peak) generation do not generally match the periods of lowest load. Critical situations thus rarely occur, and as a consequence, curtailing only a limited amount of energy can usually be sufficient to significantly reduce peak power flows at a relevant substation.

This paper discusses a decision-support method to plan such substation investment and associated generation curtailment. The goal is to discuss with the relevancy of using curtailment to differ investment at the HV/MV substation. The method uses a stochastic optimization model in which various growth scenarios for loads and generators are chosen, both in LV and MV grids.

STUDY METHODOLOGY

Principle

We consider a substation whose maximum power capacity is about to be reached, and where it is foreseen that an upgrade, and thus a costly investment, will soon be required. Our objective is to decide when the investment decision should be made, in order to minimize the global actualized expected cost. This cost includes the capital expenditures (i.e. the investment cost itself) and the operational expenditures, which take two forms: compensatory payments to generators whose energy is curtailed, and possibly some additional constant amount covering the cost of deploying the curtailment technology.

The role of the decision-support tool depicted below is to determine what the best decision is between making the investment and postponing it. In order to assess this tool, we created prospective scenarios for load and generation growth based on a simple mathematical model and from the experience of planning engineers, and we run the decision-support tool over these scenarios to assess the relevance of the investment time chosen by the algorithm compared with the optimal one. The key point here is that the optimal investment time may easily be determined a posteriori, for back-testing purpose, but is obviously not accessible to planning engineers, who only rely on (relatively unreliable) forecasts. As a consequence, the decision-support algorithm must also rely only on such
forecasts; another mathematical model was thus created to generate forecasts that predicted the chosen growth scenario with an amount of error that is consistent with the uncertainty faced by planning engineers in real life. In practice, the Distribution System Operator (DSO) would feed the decision-support algorithm with their own forecasts and decide whether or not they should defer the considered substation investment. The previous elements may be used to simulate a long-term process divided into time steps. At each step, the DSO determines the optimal decision based on their current knowledge of the situation. When this decision turns out to be: “making the investment at the current time step”, the investment is triggered and the simulation stops. The model for a complete simulation is illustrated on Figure 1.

![Figure 1 - Structure of a complete scenario simulation](image)

**Assumptions**

The scenario is simulated over a certain period of time, typically a few years. The global cost includes the capital expenditure for the investment and technology, and the operational costs. Customers and generators are connected either in low (LV) or medium voltage (MV). However power flows in the network itself are not taken into account in the study; only the power flow at substation is considered. LV and MV customers are thus treated separately only because they typically exhibit different growth characteristics, although their load and generation profile are considered identical, and because we considered that only MV generators could be equipped with curtailment technology. Generators and loads are simply modelled through their individual “power generation curve” and load curve respectively, that is to say their active power generation and consumption over time, which is supposed to be known in advance. The reason for this optimistic assumption is that the main unknown in our study is the connection of new generators to the network, which causes much larger uncertainties for planning engineers than random fluctuations of wind and solar generation for example. What is considered as most uncertain, and thus modelled using probabilistic laws, is the number of generators and loads that follow these predefined power profiles; said otherwise, the shapes of the aggregated load curve and generation curve are known, but the value of the peak power in these curves, also called production or load capacity, is subject to forecast errors. The cost for technology includes capital and operational expenditures per producer, with no residual value. As stated before, the technology may be used with MV producers only.

Generators receive compensatory payments for curtailments. Considering that measuring an amount of “non-generated energy” is difficult and that curtailment will probably be activated mainly during production peaks, the curtailed energy is accounted for as the difference between the nameplate capacity of the considered generator and the curtailment setpoint. Said otherwise, generators are compensated as if they would have produced their maximum power output, had they not been curtailed.

The DSO is supposed to have perfect knowledge of the load and generation profile and of the installed capacities at the present moment. It also has access to a probabilistic model for the future evolution of generation and load capacities (again, this model will be subject to forecast errors, reflecting the situation faced by practitioners), and to the waiting list where upcoming generators are registered. Finally, a known delay applies between the time when the DSO decides to engage the investment and the effective availability of the upgraded substation.

**Prospective model (forecasting model)**

A prospective model is a set of possible futures starting from a given time step, weighted by probabilities, to describe how the unknown parameters will evolve on the remaining time in the simulation period. Let $C(t)$ and $P(t)$ be the load and production capacity at each step $t$ of the $i^{th}$ scenario. A prospective model is called “deterministic” if it only contains one possible scenario.

**Strategy**

A strategy $X$ is a complete decision rule which, for each scenario $o$ of the prospective model $Ω$ and its probability density $p$, associates a set of decision variables $X(o)$. An optimized strategy for a given objective function $F$ satisfies the optimization problem given in (1).

$$\min_X \sum_{o \in Ω} p(o)F(X(o))$$

A strategy is non-anticipative when the decision taken at each step of time does not use information revealed in the future. It implies that if two scenarios have the same values of uncertain parameters until a certain moment,
the decisions made according to the strategy have to be identical for both scenarios until this moment. To ensure this, the scenarios are presented in the form of a decision tree. Figure 2 illustrates an example where the model includes two scenarios ABC and ABD with probabilities \( p \) and \( 1-p \) and the tree reduction model to ensure the non-anticipativity constraint.

\[
\begin{array}{c}
\text{p} & \text{A} & \text{B} & \text{C} \\
\text{1-p} & \text{A} & \text{B} & \text{D}
\end{array}
\]

Figure 2 - Prospective model compacted as a decisional tree, where A, B, C, D are possible states of a scenario

In this problem, the decision variables associated with each node of the tree are: binary variables modelling the possibility to either trigger or defer the investment, binary variables to decide whether or not generators should be equipped with curtailment technology, and real (i.e. continuous) nonnegative variables representing the amount of energy to curtail. The constraints are that each path of the tree must contain at most one investment decision and that the power flow substation should never overcome the limit.

CASE STUDY

Inputs parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean MV production growth</td>
<td>1900 kW/year</td>
</tr>
<tr>
<td>LV production growth</td>
<td>500 kW/year</td>
</tr>
<tr>
<td>Consumption growth</td>
<td>1% /year</td>
</tr>
<tr>
<td>Substation rated power</td>
<td>30 MW</td>
</tr>
<tr>
<td>Delay between decision and investment availability</td>
<td>2 years</td>
</tr>
<tr>
<td>Delay between registration of a new producer and its effective connection</td>
<td>1.5 years</td>
</tr>
<tr>
<td>Substation investment</td>
<td>1500 k€</td>
</tr>
<tr>
<td>Discount rate</td>
<td>8%</td>
</tr>
<tr>
<td>Simulation period</td>
<td>10 years</td>
</tr>
<tr>
<td>Minimal delay between two curtailment orders</td>
<td>30 mn</td>
</tr>
<tr>
<td>Curtailed energy cost</td>
<td>70€/MWh</td>
</tr>
</tbody>
</table>

A case study was implemented in order to evaluate the relevance of the proposed method. Generation and consumption profiles were created based on actual measurements made at a chosen French substation. All generators are supposed to be photovoltaic. Resulting input parameters are shown in Table 1. Delays and investment have been chosen according to past measurements, and the curtailed energy cost has the same order of magnitude as French feed-in tariffs.

In this case, the investment is low so that the DSO is supposed not to have risk aversion. The expected total cost is thus taken as the objective function.

Scenario creation

The growth of LV generation and load was supposed to be relatively predictable, at least compared with MV-side growth, and we considered that the DSO has access to perfect forecasting on the LV side of the network. Moreover when a curtailment order is sent, the short-term behaviour of producers and consumers is perfectly known which means that there will not be a violation of the power constraint, ensuring that there are enough equipped producers.

The monthly evolution of MV generation capacity follows a multinomial distribution; that is to say, for each day there is a probability for each size of generator to be registered in the waiting list. Sizes and probabilities are given in the Table 2.

In this case, the investment is low so that the DSO is supposed not to have risk aversion. The expected total cost is thus taken as the objective function.

Table 2 – Monthly producer registration in the scenario

<table>
<thead>
<tr>
<th>Production capacity</th>
<th>500 kW</th>
<th>3 MW</th>
<th>9 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability</td>
<td>7.5 %</td>
<td>2.4%</td>
<td>0.54%</td>
</tr>
</tbody>
</table>

Forecasting model

In the prospective model, three possibilities occur at each time step: no new generator registration, registration of a new generator with medium capacity, and registration of a new generator with large capacity. It means that the prospective model only considers three possible “paths” as a representation of every possibility in the scenario creation. The according sizes and probabilities are given in Table 3.
Deterministic vs stochastic decision

A possible scenario for cost is illustrated on Figure 3. The cost for delayed investment does not include the residual value at the end of the period. Three decision rules are used with the previous scenario, in order to minimize the total cost. The case “without curtailment” means that the investment has to be operational before the current limit is exceeded at substation. Deterministic optimization uses a median prospective model with only one scenario that corresponds to median growth, but it is also possible to use optimistic or pessimistic scenarios, as illustrated on Figure 4. Stochastic optimization on the contrary uses the complete prospective model, where mean and standard deviation of the unknown parameters matches the values used for generating the scenario.

The main difference between stochastic and deterministic method is the way future is perceived. The deterministic optimization means that only one scenario is planned and the decision is taken accordingly. Then the choice of this unique prospective scenario depends on the sensitivity to a bias with the real scenario. By considering the median scenario, we supposed that the risks of overestimating or underestimating production growth are identical. If there is a risk dissymmetry, the prospective scenario will be chosen in order to balance it.

Deterministic optimization is relatively simple since it requires only one forecast per time-step and little computation. However, it takes little account of uncertainties; stochastic optimization solves this problem and thus improves on deterministic optimization, at the cost of increased complexity in determining forecasts and computing solutions. Stochastic optimization generates a prospective model with different scenarios in order to capture the respective likelihood of the envisioned futures. Forecasts of total generation capacity and the associated cost evolution are illustrated on Figure 4 and Figure 5 respectively, where we depict both the forecasts made at year 3 and the actual future. Then the optimal date for investment is calculated by minimizing the total expected cost. On Figure 6, these dates are given according to the method used, stochastic decision leads to a distribution of possibility while the other methods give a unique result.

We ran the simulation of several (200) scenarios similar to the one depicted on Figure 3, and gathered statistics about costs and investment dates in Table 4. The stochastic model appears slightly more efficient than the deterministic, mostly because of the short delay between investment and new generators connection. Comparing deterministic and stochastic optimization, we notice that the difference is rather small in terms of average cost, but significant in terms of standard deviation.
Table 4 - Decision and costs on a sample of possible scenarios

<table>
<thead>
<tr>
<th></th>
<th>Mean investment date (yrs)</th>
<th>Mean total cost (k€)</th>
<th>Standard deviation (k€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without curtailment</td>
<td>3.5</td>
<td>666</td>
<td>0</td>
</tr>
<tr>
<td>Deterministic model</td>
<td>6.9</td>
<td>426</td>
<td>96</td>
</tr>
<tr>
<td>Stochastic model</td>
<td>6</td>
<td>422</td>
<td>16</td>
</tr>
</tbody>
</table>

Impact of the cost for equipping producers

An example of scenario realization is represented on Figure 7. The cost for MV technology is considered as 20 k€/generator and 2 k€/generator/year, considering that it would be mainly based on a technical study and communication devices which do not depend on the size of the generator. These figures are chosen according to an estimated order of magnitude for these costs [4]. It appears that the cost for equipping generators does not have a significant impact as long as only few generators are concerned.

CONCLUSION

In this paper, we described a decision-support tool to find the optimal compromise under uncertainty between two technical solutions to handle a power constraint. We applied this methodology to a case study based on realistic orders of magnitude and showed by example that curtailing generation to defer substation investment did allow a decrease in the mean total cost of the operation. We do not expect the cost for technology to have a tangible impact on this conclusion. By contrast, potential gains probably depend significantly on the quality of the forecasting model according to the stochastic behaviour of the real parameters. In our study, we assumed a level of uncertainty which, while realistic, is rather high: in practice, the capacity of a substation for hosting generators is also limited and/or driven by exogenous factors such as high voltage grid capacity, availability of locations for new generators, feed-in tariffs, etc. This information is normally available to the DSO and may be used for forecasting purpose. But the model is also created under strong assumptions of perfect knowledge of load and generator behaviour. As a DSO would use short-term production planning model including uncertainties, the benefit of curtailment will be lowered. Therefore, generation and load forecasting is a major issue.

REFERENCES