OPTIMAL POSITIONING AND PRE-SIZING OF STORAGE DEVICES FOR THE IMPROVEMENT OF MV DISTRIBUTION GRID OPERATION

Jean-François TOUBEAU
UMONS – Belgium
Jean-Francois.TOUBEAU@umons.ac.be

Anthony BRITO
UMONS – Belgium
Anthony.brito@gdfsuez.com

Zacharie DE GREVE
UMONS – Belgium
Zacharie.DEGREVE@umons.ac.be

Olgan Durieux
Ores – Belgium
Olgan.durieux@ores.net

François Vallée
UMONS – Belgium
Francois.VALLEE@ umons.ac.be

Jacques LOBRY
UMONS – Belgium
Jacques.LOBRY@umons.ac.be

ABSTRACT

This paper presents an innovative method based on the Experimental Design method for improving the flexibility of distribution grids through the integration of storage utilities. The purpose of the proposed procedure is to minimize the total line losses that are costly for the distribution system operators (DSOs) while respecting the quality of power delivered to end-users. To that end, a two-step process is implemented. The first part focuses on the optimal positioning of storage devices into the network whereas the second part consists in a pre-sizing of the energy capacity of the utilities. This information is indeed of great interest for the DSOs eager to invest in the most appropriate storage technology for improving the long-term operation of its grid.

INTRODUCTION

With the worldwide progressive increase of the energy consumption, the introduction of new generation units in the electrical grid becomes compulsory. Furthermore, the loss of interest in fossil and nuclear energies combined with the liberalization of electricity market leads to a massive insertion of renewable energy generation in distribution systems. Such a situation induces a modification of the historical operation of the medium-voltage (MV) network with the appearance of unusual issues such as overvoltages and line congestions. It is therefore essential to find efficient and sustainable solutions in order to cope with those problems. Currently, the most popular strategies used to solve such issues are the on-load tap changer of transformer and the reactive power compensation devices whereas the load-shedding (in the event of overload) or power curtailment (in the event of oversupply) should only be used as a last resort because of the financial repercussion of such measures. However, the transformers are not necessarily directly managed by the distribution system operators (DSOs) (i.e. most of the Belgian transformers are the property of the transmission system operator (TSO)), and reactive compensators are often costly and susceptible to increase line power flows. In this context, the introduction of storage devices constitutes an efficient and cost-effective solution [1].

The energy storage devices allow therefore facing efficiently the fluctuation of the energy generation without implementing a complicated strategy of load management or calling on rapid response plant. Such a solution is indeed often cost-expensive, inefficient and very polluting [1]. Furthermore, several technologies can be considered depending on their characteristics and on the desired objective. For static duties, the power output and the energy capacity are the main parameters whereas the response time and the discharge duration are more important in the context of transient stability. The economic aspects as duration time, investments and maintenance costs have also to be envisaged for the optimal choice of the storage technique. Currently, DSOs seems to favor the battery applications but technological advances in other technologies such as hydrogen storage could change this situation.

In this work, storage devices are optimally located in order to provide services to the distribution grid under steady-state conditions. Practically, an innovative method is developed with a long-term perspective in order to minimize the total losses in the grid that are costly for the DSO while respecting the voltage constraints defined by the European Standard EN50160 [2].

This paper is organized as follows. Firstly, the global methodology for optimally locating storage devices is explained. The principle relies on an innovative use of the screening process of the design of experiments (DOE) methodology. Then, a pre-sizing of these devices is performed in order to obtain a first estimate of the energy capacity of the utilities. This second step allows thus the DSO to evaluate whether the envisaged solution is cost-effective. The proposed approach is then carried out on an existing Belgian MV network and a sensitivity analysis for assessing the robustness of the results is performed. Finally, the perspectives are discussed.

OPTIMAL POSITIONING OF STORAGE DEVICES

In the first part, a selection procedure of the optimal location of storage facilities into the network is carried out by using the screening process of the DOE methodology. It is indeed a powerful tool for determining the effects of multiple inputs (factors) on a desired output (response of interest) through a polynomial modeling of this response [3]-[4]. In this study, the response is the total sum of the line losses and constituted thus the objective function to be minimized. Those losses are computed as follows:

$$P_{loss} = \sum_{i=1}^{L} R_i I_i^2 \quad (1)$$

where R_i and I_i correspond respectively to the resistance and the current flowing in each of the L lines.
Furthermore, beyond its simplicity of implementation, this DOE approach presents two interesting assets [5]. Firstly, it defines the lowest amount of experiments to perform in order to obtain the best precision possible on the associated model. The realization of an experiment consists here in performing a load-flow calculation on the studied distribution network, so as to obtain the total line losses. And secondly, the coefficients of this model are easily interpreted as they represent a quantitative reflection of the effect of the considered factor(s) on the response. This interesting and useful property is illustrated in Figure 1 for K=2 factors (x_1 and x_2).

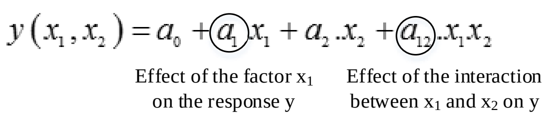

Figure 1 - *Representation of the physical meaning of the coefficients of the modeling of the response of interest.*

The number K of factors of the analytical model is equal to the number of storage units that are considered. Each factor is characterized by a range of variation usually expressed in coded variables according to the [-1, 1] interval. The values of the factors x_i correspond therefore to the output power of the storage devices.

General principle of the developed methodology

Taking into account the aforementioned considerations, this study proposes an original selection process of the optimal location of storage facilities. The general structure is represented in Figure 2.

Definition of the positioning configurations

The screening process is performed for all the possible locations of the n devices in the considered network. For a network with N nodes, $N_s = N!/n!(N-n)!$ configurations (of storage devices location) are therefore investigated in order to infer the most appropriate one for reducing lines losses. In each configuration, 2^n experiments are carried out, as a two-level full factorial design is employed because of its interesting aforementioned properties.

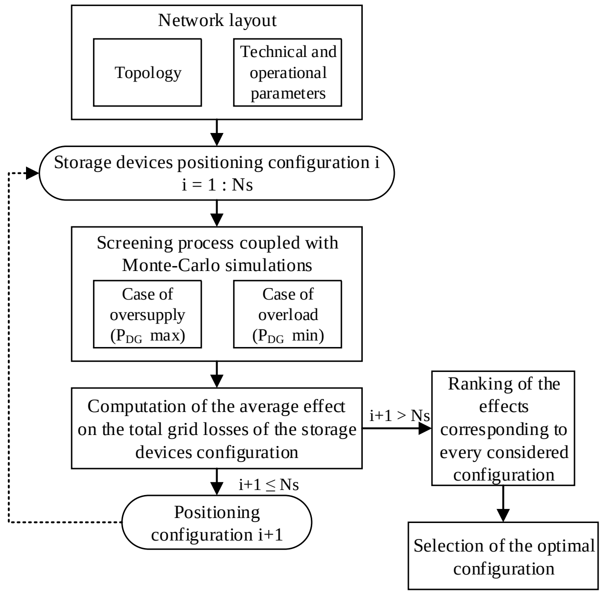

Figure 2 - *Flowchart of the determination of the optimal combination of storage devices to install into the grid.*

Definition of the two extreme generation cases

The selection procedure is divided into two complementary screening processes in order to evaluate with equal prominence the impact of charging or discharging the storage utilities. Such a strategy is indeed essential as there is a substantial fluctuation over time of the power generation (depending partly on the stochastic nature of the weather conditions) and of the total consumption (depending on the uncertainties related to consumption patterns).
Both considered cases are depicted in Figure 3 and allow separating the estimations of charge and discharge's impact of the storage devices on the total line losses.

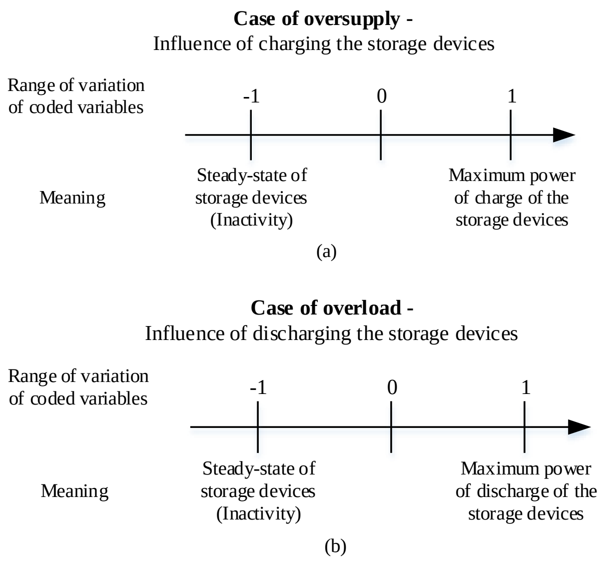

Figure 3 - *Illustration of the two-stage decomposition of the screening process.*

Explanation of the screening process implemented in a MC environment

In order to account for the non-deterministic effects of the load profiles in our study, both extreme generation cases are implemented in Monte Carlo environments. In order to obtain a good trade-off between the convergence threshold on the results (usually < 0.1%) and the computation time, it is shown that simulating 10,000 system states is the best option [6]. The developed process simulates thus, for each experiment, the random behavior of the different customers by the means of a random sampling of the consumed power at each load bus.

The total impact of the considered positioning configuration on the total grid losses is then computed by averaging the global effects provided by each screening procedure on all the Monte Carlo iterations.

It is important to clarify that the global effect of the introduction of several storage devices is calculated as the sum of the contribution of each device. For instance, when n=2 utilities are considered (Figure 1), the global effect is equal to $a_1 + a_2$.

Selection of the optimal configuration

Once the total impact of each configuration is computed, the ranking of the different positioning possibilities is easily inferred.

Definition of the scenarios

In this work, the procedure is performed for different scenarios of penetration rates of storage devices. Such an approach allows indeed a comparison between a centralized and a distributed repartition of the storage capacities. Furthermore, it gives a range of possible solutions that can be compared in order to obtain the best trade-off between installation costs and impact on the grid operation. Finally, it constitutes a robust process that can therefore be applied to any MV network whatever its size and topology.

PRE-SIZING OF THE STORAGE DEVICES

The second step consists in a pre-sizing of the installed capacity of the storage devices. This process is carried out by solving, for each hourly time-step of a typical year, an optimization problem which aims at minimizing the total grid losses under operational constraints. In this process, no upper-bound of the storage capacity is fixed, and the maximum energy value reached by the different utilities during the state-by-state optimization yields the desired pre-sizing. The typical year is defined by the statistical profiles of every component connected to the network (classical customers, DG units, MV/LV transformers). The construction of those statistical profiles is inferred from data coming from the Belgian DSO.

It is important to emphasize that this procedure does not constitute a real-time management of the storage devices but has as main objective to provide a good estimate of the storage energy capacities for ensuring an optimal grid operation.

The optimization problem can be formulated as the following constrained nonlinear multivariable function:

$$\forall t = 1,\ldots,T, \text{ solve } \min_{P_{SD,k}(t)} \left| S_{loss}\left(P_{SD,k}(t)\right)\right| \quad (2)$$

subject to:

$$0.9U_{rated} < U_i\left(P_{SD,k}(t)\right) < 1.1U_{rated}, \quad i = 1,\ldots,N \quad (3)$$

$$I_l\left(P_{SD,k}(t)\right) < I_{nom,l}, \quad l = 1,\ldots,L \quad (4)$$

$$-P_{SD,k}^{\max} < P_{SD,k}(t) < P_{SD,k}^{\max}, \quad k = 1,\ldots,K \quad (5)$$

$$0 \le E_{SD,k}(t) < \infty, \quad (6)$$

with:

$$E_{SD,k}(t+1) = E_{SD,k}(t) + P_{SD,k}(t)\Delta t \quad (7)$$

where $P_{SD,k}$ and $E_{SD,k}$ represent respectively the power and the energy capacity of the storage device k. In this work, the considered time interval Δt is of one hour and the nominal voltage U_{rated} and line currents $I_{nom,l}$ are given by the DSO.

The problem is solved by using the interior-point algorithm. With this estimate of the storage utilities capacity, the DSO is then able make an investment decision as regards the economic, geographical and politico-economic constraints.

APPLICATION ON AN EXISTING MV NETWORK

The methodology is tested on a radial 10 kV distribution network, represented in Figure 4, 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 a technical incident such as a short circuit or a problem of the transformer.

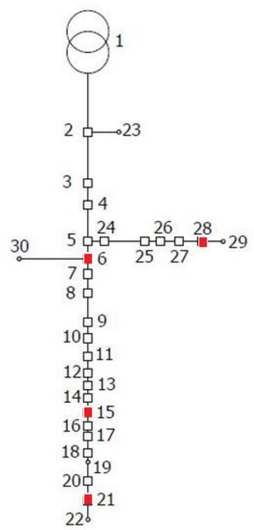

Figure 4 - *Representation of the studied MV network.*

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. Consequently, in order to avoid an heavy and expensive reinforcement of the grid, the introduction of storage facilities constitutes an important solution to investigate.
Firstly, the scenario for which the DSO is interested in investing in only one storage device is studied. The results of the screening process are illustrated in Figure 5. A bar chart representation is privileged for its simplicity. Indeed, the height of a bar represents the effect on the response of interest of the considered factor while all the other factors are considered as constant [5]. Therefore, the higher is the bar associated to a factor, the most influential (and thus efficient) is this factor.

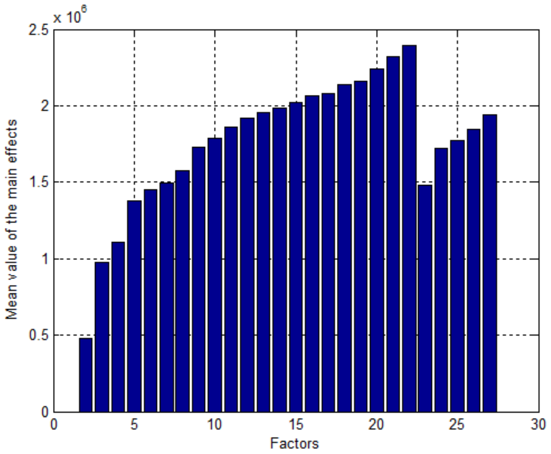

Figure 5 - *Influence of the installation of a storage devices for the nodes of the grid.*

One can see that the most beneficial locations for installing a storage utility are at the end of the main feeder of the line, namely where the line impedance has its maximal effect.
As regards the pre-sizing of the storage unit located at the node 22, the simulation yields a capacity of 5.2 MWh, which is quite important compared to the annual reduction of line losses of around 8 MWh. Such an oversizing comes from the nature of the optimization process that does not take the future into account. In this way, the control of the unit could be improved by implementing a global strategy based on a stochastic dynamic programming.
However, thanks to the presence of storage, all the voltage and congestion issues previously encountered at some nodes of the grid are eradicated. This is highly beneficial for the long-term grid operation even though this profit can hardly be financially estimated.
For the scenarios characterized by the integration of several storage units, the number of investigated solutions is too high to be clearly graphically represented. Therefore, the results of the positioning and pre-sizing processes are presented in Table 1.

Table 1 – *Summary table of the results.*

scenarios	Most influential node	Pre-sizing capacity [kWh]	Total line losses without storage [MWh/year]	Total line losses with storage [MWh/year]
1	22	5263	71	63
2	21	653	71	43
	22	4380		
3	20	690	71	41
	21	2866		
	22	2779		

From this results, one can conclude that there is an optimal number of storage devices to install within the grid as regards the minimization of line losses under operational constraints. Indeed, the introduction of a third storage unit does not significantly improve the operation of the network. Moreover, it is obvious that the DSO is subject to financial limitations and will be more interested in a compromise between a good operation of the network and the costs related to the installation, the operation and the maintenance of the storage devices. Such a situation emphasizes therefore the importance of our different considered scenarios that gives several possibilities to the DSO which can opt for the best option according to its financial resources and the magnitude of the problems encountered in the grid.
A sensitivity analysis is then performed in order to assess the reliability and the robustness of the proposed solution facing an increase of the renewable energy generation. To that end, a large DG unit is added at node 11 of the network and the same two-step procedure is carried out.
As expected, this integration does not change the conclusions of the study and the extreme nodes of the grid are still the most influential. However, the effect of the storage devices on the reduction of line losses is then increased which constitutes another incentive for the DSO to invest in this means of flexibility in the most critical areas of the distribution grid.

CONCLUSIONS AND PERSPECTIVES

This paper was devoted to the integration of storage devices with the DSO perspective of improving the operation of the MV network. Indeed, increasing the storage capacity now stands as an excellent solution for strengthening the electrical grid in order to cope with the massive integration of non-predictable generators.
The proposed approach highlighted that the most beneficial nodes for installing a storage device are located at the end of the feeders. However, the pre-sizing procedure led to a blatant oversizing of the utilities. It is therefore of high interest to implement a strategy based on dynamic programming to optimally control the storage devices by taking into account the future network states

when controlling the unit at a specific time.
The sensitivity analysis then illustrated the good stability of the proposed solution to an ulterior introduction of generation within the grid.

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