ANALYSIS OF THE OPTIONS TO REDUCE THE INTEGRATION COSTS OF RENEWABLE GENERATION IN THE DISTRIBUTION NETWORKS. PART 2: A STEP TOWARDS ADVANCED CONNECTION STUDIES TAKING INTO ACCOUNT THE ALTERNATIVES TO GRID REINFORCEMENT.

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ABSTRACT

This two-part article deals with the latest results of a joint research effort by ERDF and EDF R&D to assess the cost of DG/RES integration and study new solutions that may help to reduce it. The companion paper ("Part 1") analyses the connection costs of RES in France on 2012-2020 and 2012-2030 scenarios, as well as the global savings that could be made possible by some innovative RES integration solutions. This paper ("Part 2") focuses on an innovative planning tool under development that allows searching the best option on a case-by-case basis.

INTRODUCTION

The integration of Renewable Energy Sources (RES) into distribution networks impacts the way the power flows along the feeders. Grid connection studies allow DSO to quantify these effects and, whenever necessary to prevent current and/or voltage limit violations, the grid is upgraded to accommodate new generators. Grid reinforcement takes time and has a cost for the collectivity: for instance, the study presented in the companion paper [1] shows that each additional MW of RES in France has an average cost between 100 k€/MW (wind) and 300 k€/MW (PV). Moreover, the situation will worsen in the years to come since the favourable cases –*i.e.* feeders with some remaining hosting capacity– will become scarce as the penetration levels of distributed generation increase. Therefore, it is required to develop and assess new solutions to reduce the costs of integrating RES into distribution systems.

Several of these alternatives to grid reinforcement (such as generation curtailment, storage, *etc.*) are already well-documented. However, all these solutions must still be compared to each other so that their relative worth can be determined. The companion paper ("Part 1") analyses the connection costs of RES in France and the economics of some of the considered innovative options on multi-year scenarios (*e.g.* 25 GW of PV in France in 2020). Complementarily with this global approach, the present paper ("Part 2") focuses on an innovative planning tool under development that allows establishing, for any connection request at MV level, the merit order of the alternatives to grid reinforcement. To this end, it first gives an overview of the solutions to integrate DG/RES in distribution grids. Then, the proposed approach is quickly described before being applied to a case study.

OVERVIEW OF POSSIBLE SOLUTIONS TO INTEGRATE RES IN DISTRIBUTION GRIDS

Table 1 reviews both the technical solutions currently in use in France to integrate DG/RES and other, newer alternatives that can be considered. The operating principle of each of them is described, as well as their key advantages, their economics and their current status in France. All these solutions can eliminate node voltage violations. However, only solutions 1, 5 and 6 are useful in case of branch current limit violations. Apart from usual grid reinforcement, only solution 2 is currently deployed in the French MV grids. This said, whenever possible, ERDF also decreases the set point of the On Load Tap Changer (OLTC) at the HV/MV substation down to 1.02 p.u. (20.4 kV) to facilitate DG/RES integration. Considering that this set point remains constant through the year, this is the lowest possible value that can be applied without creating a risk of voltage drop issues.

A TOOL TO ASSESS THE MERIT ORDER OF ALTERNATIVES TO GRID REINFORCEMENT

Description of the proposed approach

At present, the connection studies carried out by ERDF follow the so-called "deterministic methods", also referred to as "worst-case approaches". These are well suited for the analysis and robust design of RES integration solutions of types 1 and 2, but are not adapted where it comes to the study of most of the alternatives to grid reinforcement.

The innovative planning tool under development at EDF R&D –within Matlab environment– aims at making possible to analyze the merit order of various grid integration solutions of DG/RES. To this end, starting mainly from readily available data (10-minute time series from ERDF monitoring system), the operation of the feeder concerned by the connection request is simulated over at least one year using a sequential load-flow algorithm. When the grid cannot evacuate the power of the studied generator, the alternatives to grid reinforcement selected by the user are activated. Each of these solutions can thus be fully characterized (time series of curtailed power, *etc.*).

n°	Solution	Principle	Key advantage(s)	Source(s) of cost	Status in France
1	**Distribution grid reinforcement**	Increase the hosting capacity of the grid by upgrading existing assets and/or putting new circuits into service (e.g. dedicated feeder)	Adapting the grid is the most robust way to integrate DG/RES Tend to reduce grid power losses in comparison 2-6 (lower resistance)	Grid CAPEX Grid OPEX (maintenance of the additional circuits, but less losses) Time delay	In use
2	**Reactive power control at the Point of Common Coupling (PCC): constant Power Factor (PF)**	Avoid voltage limit violations by controlling the reactive power at the PCC under constant power factor (tan(φ) control: Q_{gen}=tan(φ).P_{gen})	Simple and robust: a local control loop maintains tan(φ) at a constant set-point calculated by the DSO during the connection study	Increase in the MVA rating of generators Increase in grid power losses (additional reactive load)	In use in MV grids (-0.35≤tan(φ)≤0.40)
3	**Reactive power control at the PCC: advanced approaches such as *Q*=f(*U*) algorithms**	Avoid voltage limit violations by controlling the reactive power at the PCC using advanced (e.g. *Q*=f(*U*)) algorithms (local or remote control)	Although tougher than 2 to design, the option 3 makes a smarter use of reactive power control by restricting its use to when it is the most needed	Increase in the MVA rating of generators – same as solution 2 Increase in grid power losses (additional Q – less than solution 2)	Field test started both in LV and MV grids in 2011/2012 by ERDF and EDF R&D
4	**Real-time control of the On-Load Tap Changer (OLTC) reference voltage at the HV/MV substation**	Avoid voltage limit violations by controlling continuously the reference voltage of the OLTC, in spite of a constant reference value	Powerful option capable of solving voltage rise issues without creating low voltage limit violations thanks to distribution state estimation	Require a network of sensors and an advanced control at the HV/MV substation Extra maintenance of the OLTC	Field test started in 2012 by ERDF and EDF R&D
5	**Generation curtailment**	Avoid voltage limit violations by curtailing or even disconnecting temporarily DG/RES (local or remote control)	No extra CAPEX	Loss of generation due to curtailment of "as-available" DG/RES	R&D
6	**Distributed Energy Storage Systems (DESS)**	Avoid voltage limit violations thanks to DESS: the energy in excess is stored locally in order to be injected to the grid whenever possible	Less loss of energy than option 5 (only roundtrip power losses) Possible aggregation of several functions to increase profitability	DESS CAPEX DESS OPEX (power losses, maintenance, etc.)	R&D Field test to start in 2013 or 2014 in ERDF networks

Table 1. Description of various possible solutions to integrate RES in distribution systems.

Figure 1 presents a sample of the time series calculated by the proposed tool to analyse the connection of a PV plant without reinforcement thanks to generation curtailment. This solution is studied under 3 forms: temporary disconnection, curtailment at constant power factor (PF) and curtailment at minimum reactive power output. When a voltage limit violation is found anywhere in the studied grid, the tool computes the amount of curtailment that is required to bring the voltage back to (or below) the 1.05 p.u. limit.

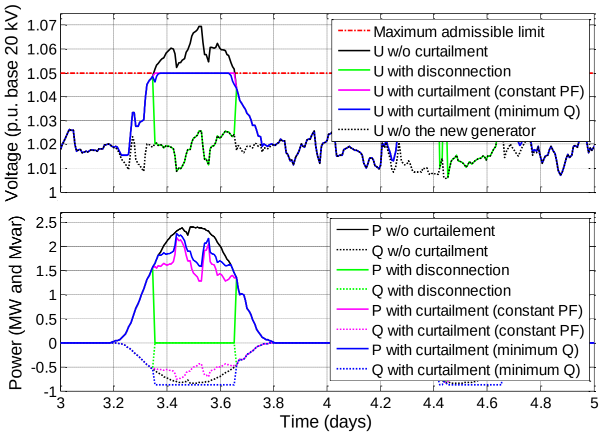

Figure 1. Sample result of the connection study of a PV plant (analysis of generation curtailment). Upper figure: voltage at the connection point. Lower figure: active and reactive power output of the studied PV plant.

Inputs and outputs.

The required inputs are grid data (topology, impedances, *etc.*) and at least 4 time series: active and reactive power of the loads (if required, each load can have its own particular profiles), power injected by the studied RES and voltage at the HV/MV substation. The simulation results allow calculating the net present cost of each considered solution.

CASE STUDY: GRID REINFORCEMENT VS. CURTAILMENT VS. STORAGE FOR THE CONNECTION OF A PV PLANT TO THE GRID

Description of the case study

Main objectives

To illustrate the interest of the new approach under consideration, the proposed tool is used in this paragraph to determine the merit order of 1/ grid reinforcement, 2/ curtailment and 3/ storage for the connection of a MW-scale PV plant to the end of a rural MV feeder. To characterize the impact of the penetration level of generation on the merit order of these 3 types of options, the rated power P_{gmax} of the new generator is varied between the hosting capacity of the feeder and around four times this value.

Studied MV distribution network

We study the connection of a new RES plant at the end of the MV (20 kV) feeder depicted in Figure 2. Located in a rural area –with space for PV or wind generation–, this 3-phase 3-wire feeder is rather long (30 km), mainly composed of overhead lines with a moderate cross-section area (54 mm^2) and weakly loaded (< 1 MW). The total impedance between the connection point of the new RES plant and the HV/MV substation is 10.66+j.6.97 Ω. The generation **hosting capacity at the end of the feeder is 1,1 MW** (under tan(φ)=-0.35), limited by voltage rise issues.

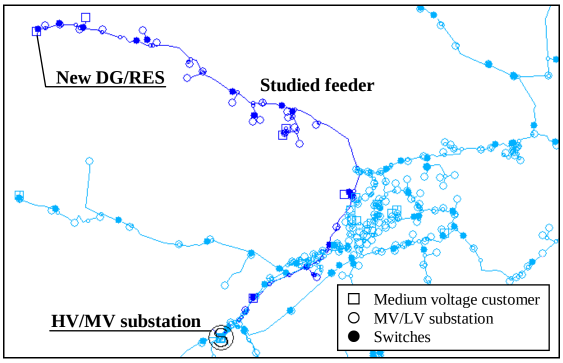

Figure 2. MV feeder under consideration.

Time series of load, PV power and substation voltage

This illustrative study is performed using 10-minute time series over one year. The PV generation data was recorded at a MW-scale plant located in the south of France. The data was normalized to the rated power of this generator (p.u. in base P_{gmax}), so that it can be scaled to any comparable plant size in this study. The annual output of this PV system is around 1600 kWh/kWp, which is on the high end of what is feasible in France. The time series of load data –active and reactive power illustrated in Figure 3– was recorded at the beginning of a feeder very similar to the studied one. In our simulations, we consider that the total load is distributed among the buses of the grid in proportion to their peak load.

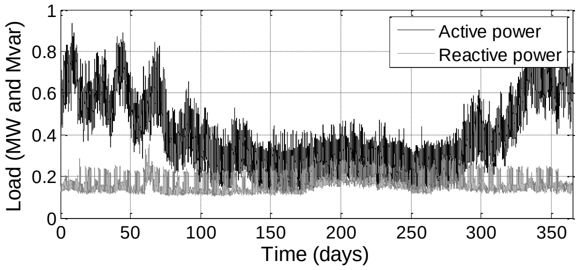

Figure 3. 10-minute time series of the feeder load.

The time series of voltage fluctuations at the HV/MV substation was recorded at the same place as the load; the data follows a normal distribution with a mean of 20.4 kV (set point of the OLTC) and a standard deviation of 0.1 kV.

Technical results obtained with the proposed tool

Apparition of voltage limit violations

The tool described above is used to analyze the connection of a new PV system to the studied feeder. The rated power P_{gmax} of this RES plant is increased from 1.1 MW to 4 MW by an increment of 250 kW and its impact on the voltage profile is characterized. For example, Figure 4 shows the empirical probability distribution of the voltage at the end of the studied feeder before and after the connection of a 2.5-MWp PV plant. In this case, the voltage appears to be over the maximum admissible limit of 1.05 p.u. around 10 % of the time and violations of over 0.02 p.u. are found.

The risk of node voltage limit violation as a function of the rated power of the PV plant is shown in Figure 5. Under our assumptions, it remains moderate for a PV system of less than 1.75 MWp, but rises fast as soon as the rated power of the plant exceeds this value. The proposed tool allows contemplating various ways to eliminate these voltage violations (see Table 1). Due to space constraints, only curtailment and energy storage are considered herein.

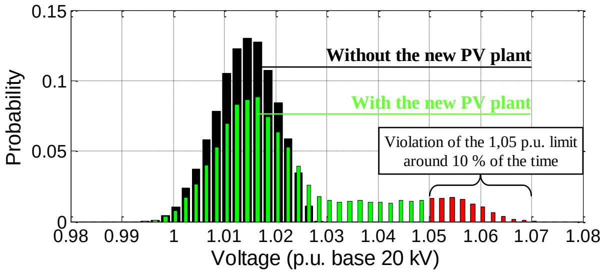

Figure 4. Probability distribution of the voltage at the connection point of the new PV plant (2.5 MWp).

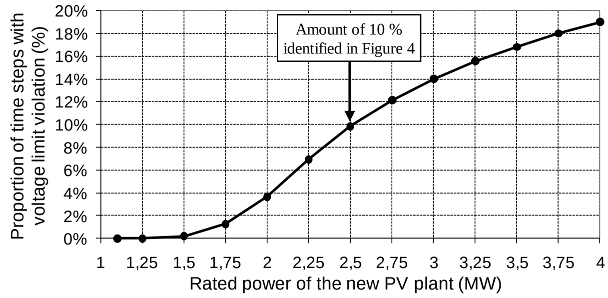

Figure 5. Risk of voltage limit violation vs. rated power of the new PV plant connected to the studied feeder.

Alternative to reinforcement: generation curtailment

As illustrated in Figure 1, this solution is included in the proposed approach under 3 possible forms: disconnection of the generator to avoid voltage violations, curtailment at constant PF and curtailment at minimum reactive power output (-0.35.P_{gmax}). These 3 options have been studied with the tool: Figure 6 shows the marginal curtailment as a function of the rated power of the PV plant. Considering an arbitrary limit of 20 % (an extra kW of PV curtails a fifth of its available energy), we found that disconnection leads to unacceptable levels of loss of energy below 1.75 MWp. Curtailment is less penalizing, and thus remains a possible alternative to grid reinforcement up to 2.25 MWp (constant PF) and 2.5 MWp (constant Q) in the studied case.

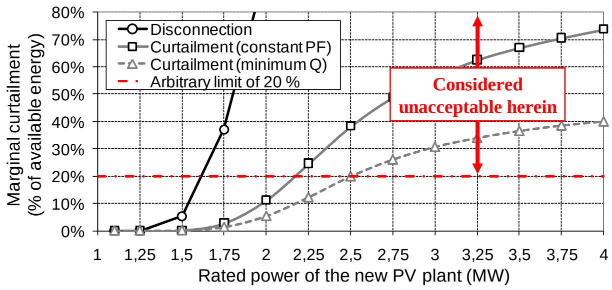

Figure 6. Marginal energy curtailment vs. rated power of the new PV plant.

Alternative to reinforcement: energy storage systems
Since wind and PV are "as-available" sources, any curtailed energy is definitely lost. If a DESS is used as an alternative to grid reinforcement, the energy that cannot be evacuated when it is available is stored in order to be injected to the network whenever possible. The proposed tool can calculate the time series of the power exchanged by a storage unit with the grid in order to eliminate voltage violations. This time series is then analyzed to calculate the rated power and energy of the DESS. The result of this process in the studied case is depicted in Figure 7. For instance, it is required to put a storage unit of 0.8 MW / 2.2 MWh to connect a 2.5-MWp PV plant to the grid without reinforcement.

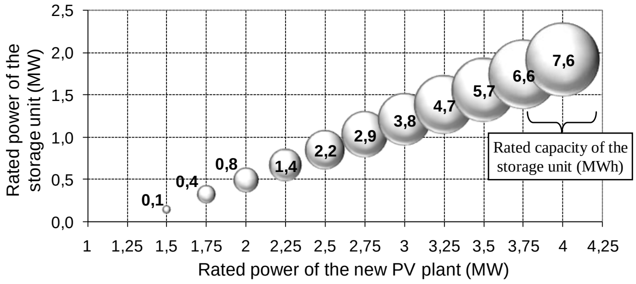

Figure 7. Required rated power/energy of the storage unit vs. rated power of the new PV plant.

Expression of the results in economic terms

The technical outputs of the proposed approach make it possible to calculate the economic merit order of the considered solutions to connect the studied PV plant to the grid. The economic appraisal presented in this last paragraph takes into account, whenever relevant, the costs of MV grid development, of line losses, of curtailed energy, of the storage unit, as well as the residual value of the assets at the end of the lifetime of the PV plant. An overview of the main hypothesis is given in Table 2.

Financial and miscellaneous	
Project lifetime	20 years
Discount factor	8 %
Line losses	70 €/MWh
Curtailment	
Value of PV energy	200 € per MWh of curtailed energy
Energy storage	
Initial/replacement cost	750 k€/MW + 300 k€/MWh (-2 %/year)
Lifetime	15 years
Roundtrip efficiency	75 % ac/ac
Maintenance cost	2 % of the initial investment per year

Table 2. Hypothesis of the economic analysis.

The final result of this case study is presented in Figure 8. The orders of magnitude regarding grid reinforcement –up to 400-450 k€/MW– are rather consistent with those calculated by ERDF in the companion paper [1] for MV generation in unfavourable areas. Above 2 MWp, a dedicated feeder of more than 10 km must be put in place. As it remains the same for larger PV systems, the grid reinforcement cost per MW of generation then decreases as a function of the rated power of the plant. Under our assumptions, it appears that storage, punctual disconnection, as well as an optimal combination of both, are rather expensive in comparison with the other options. However, it should be kept in mind that this study does not take into account the possible aggregation of DESS benefits (see [2]).

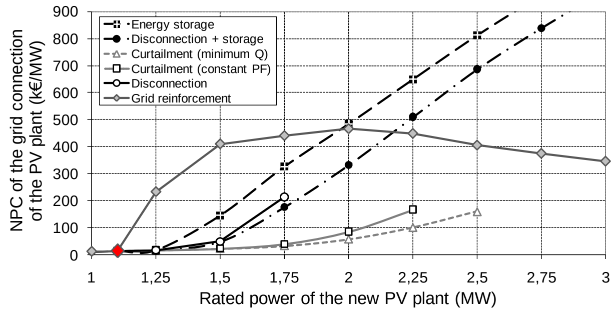

Figure 8. Net Present Cost (NPC) of each studied solution vs. rated power of the new PV plant.

Between 1.1 MWp and 2.5 MWp, curtailment seems to be a promising solution to extend the hosting capacity of the grid in this case study –which, again, is not representative of the average costs presented in [1], presumably because of the long and weak feeder considered in this paper–. Above 2.5 MWp, we consider that curtailment is no longer viable due to excessive marginal loss of energy. Therefore, grid reinforcement becomes the most interesting option.

The attractiveness of the alternatives to grid reinforcement can vary from these results: ref. [1] states that curtailment can decrease the connection costs of PV by 30 % on average. **Our main conclusion is that a tool such as the one described herein is needed to realize advanced grid connection studies on a case-by-case basis. In addition, as discussed in [1], regulatory changes are required.**

CONCLUSION AND FURTHER WORK

This paper briefly presents a tool under development at EDF R&D to include various alternatives to grid reinforcement in connection studies of DG/RES. Ongoing, further research includes work on how to ensure a sufficient level of statistical representativity (minimum length of the time series, *etc.*), sensitivity studies and the first steps of development towards the implementation of the proposed approach within ERDF planning tools.

REFERENCES

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[2] G. Delille, B. François, G. Malarange, JL. Fraisse, "Energy storage systems in distribution grids: new assets to upgrade distribution system abilities", *Proceedings CIRED 2009*, paper 0493.