NON-FIRM GRID CONNECTIONS FOR LOW-VOLTAGE GENERATORS: A CASE STUDY

Louise MULLER
Roseau Technologies – France
louise.muller@roseautechnologies.com

Florent CADOUX
Roseau Technologies – France
florent.cadoux@roseautechnologies.com

ABSTRACT

Since 2021 in France, non-firm connection offers to the distribution grid must legally be made available to connection applicants at their request. This type of flexible connection, which is especially suitable for generators, is indeed considered as a way to reduce the costs and delays that hinder the development of distributed renewable energy resources. In practice however, non-firm connections are only emerging, and there is still some debate regarding how frequently this approach would make economic sense - especially at the low-voltage levels where the individual economic stakes are low. We investigate this issue by analysing the relevance of non-firm grid connection for a set of real-world LV-level photovoltaic projects.

NON-FIRM GRID CONNECTIONS

A "non-firm grid connection" is defined as a contractual agreement between the Distribution System Operator (DSO) and a (usually new) customer, whereby:

- the DSO accepts to connect the new customer to the existing grid without reinforcing it, in cases where grid reinforcement should normally take place according to the standard procedure;
- and the customer accepts to undergo occasional power curtailments in order to mitigate potential grid congestions.

This arrangement is particularly relevant for generators, as opposed to loads, since generation curtailment is usually unobtrusive and relatively easy to implement. The remainder of this paper thus focuses on non-firm grid connections for generators, solely.

Non-firm connections make economic sense in situations where connecting the new generator to the grid would create a mild constraint, that is to say a constraint that would not be too deep nor too frequent. In such a case, grid reinforcement can be avoided by curtailing only a limited amount of energy, hence by incurring a limited and acceptable loss-of-gain for the producer. An important question, on which our study below sheds some light, is whether this situation is frequent in practice: how often would real-world producers find it economically beneficial to choose the non-firm connection option rather than the standard (firm) one?

The answer to this question obviously depends on the rules that determine which share of grid costs are born by the connection applicant. In some countries, the price of grid connection for the applicant is fixed, regardless of the actual cost of the required grid works. In other countries, such as France, the price paid by the applicant for grid connection partially reflects the actual cost of the required grid works.

It thus happens, in the latter case, that the cost of (firm) grid connection may be prohibitive for the potential producer. This situation, on which we focus below, occurs when the required grid works are so costly that paying the price of grid connection would make the generation project uneconomical. In such cases, the applicant normally cancels their generation project unless a cheaper alternative can be found.

Non-firm grid connections have long been considered such a potential alternative. As such, they have recently entered the French legislation: Order of July 12th 2021, implementing Article D. 342-23 of the French Energy Code, states that:

"... at the request of the (...) connection applicant, the grid operator proposes, if the network capacities allow it, an alternative connection offer (...) [for which] the minimum non-guaranteed power for injection is less than or equal to 30% of the requested connection power; [and] the annual curtailed energy does not exceed 5% of the annual production of the generator."

In other words, whenever voltage and current constraints on the grid can be avoided by curtailing no more than 30% of the generator's capacity at any time, and no more than 5% of its energy annually (hence reducing the producer's revenue by no more than 5%), non-firm grid connection should be made available to grid users.

In practice, non-firm grid connections currently are indeed in use (although not in a widespread manner) in France for the connection of large generators to the medium-voltage (MV) grid. As far as the low-voltage (LV) grid is concerned, however, and in spite of the above-mentioned Order of July 12th 2021 that applies to all voltage levels indistinctly, non-firm grid connections are not yet implemented by French DSOs and thus not yet offered to grid users [1].

This paper describes a case study that we carried out in order to assess the feasibility of extending non-firm grid connections to the LV level.

CASE STUDY

Context and motivation

The case study was commissioned by a Local Authority responsible for overseeing the distribution of electricity in a geographical area amounting to roughly 1% of the national territory. Eager to support the development of renewable energy projects over its territory, the Local Authority decided to analyse in detail a few dozen LV-level photovoltaic projects that had recently been abandoned by their stakeholders due to prohibitive (firm) grid connection prices, as described above. The objective was to assess whether some of these projects would have been economically viable, if the non-firm connections ruled by Order of July 12th 2021 had actually been available at the LV level.

Data

It is worth noting that the original (firm) grid connection studies had been carried out by the local DSO, from which the Local Authority is entirely independent. As a consequence, the Local Authority only has access to the result of the connection study that was performed by the engineering team of the DSO for each of the various study cases; the details of the analysis itself were not provided by the DSO to the Local Authority.
Nonetheless, the Local Authority has access to detailed grid data such as the GIS data that describes the topology of the grid, the physical characteristics of lines, the rated power and tap settings of HV/MV and MV/LV transformers, etc. The data necessary for the modelling of the grid was thus fully available. The Local Authority has also access to data related to the loads and generators that are already connected to the distribution grid. The Local Authority thus has access to all the necessary information to perform its own assessment of the available grid connection options, by means of power flow analysis at the MV as well as LV level.

ASSUMPTIONS

General assumptions

For simplicity, the study was limited to comparing the firm connection, that involves grid reinforcement, with a purely non-firm connection, that involves no grid reinforcement at all. Intermediate solutions, based on a combination of generation curtailment and grid reinforcement, were not studied.
All the new generators under study requested a three-phase grid connection, including small units for which a single-phase connection would also have been allowed. All generation units were thus modelled as three-phase.
Whenever existing generators were connected to the grid, generation curtailment was only applied to the new generator under study. Legacy generators were not assumed to participate in the non-firm scheme.
Firm connection analysis was performed using the DSO's standard methodology of performing a single power flow calculation where generators are at peak power and loads are at minimum power. Non-firm grid connection analysis was performed using a time series approach over one year, with 1 hour time steps; this more elaborate approach is made necessary by the need to cumulate the curtailed energy over time in order to check that it does not exceed 5% of the total producible energy.
LV-level power flow analysis was performed using unbalanced three-phase modelling. MV-level power flow analysis was performed using balanced, single-phase equivalent modelling.
The maximum allowed voltage in France is 110% of the nominal voltage at the delivery point of the customer. Given that a fixed 1.5% voltage margin is reserved for the "last cable" that goes from the LV feeder to the customer's delivery point, power flow analysis is carried out on the LV feeders only, without modelling the "last cable", and using a maximum voltage limit of 108.5% at any point on the LV feeder. This assumption is generally detrimental to non-firm connections since the actual voltage rise in the last cable is normally lower than the 1.5% margin; however, we were not able to take this factor into account due to the lack of data about the characteristics of the cables.
Finally, when analysing our simulation results, we considered that a non-firm connection was "successful" if and only if it met the conditions of the Order of July 12th 2021; namely, if grid constraints could be fully avoided without curtailing more than 30% power and 5% energy. From the point of view of the producer, whose problem is essentially economic, it may be more meaningful to check whether the amount of shed energy was actually low enough to make the project economically profitable. This approach is however both more complex, and more arbitrary in the sense that each producer has their own definition of the "minimum acceptable level of profitability" of their generation project. The 5% limit ruled by the Order of July 12th 2021 was thus adopted as an acceptable proxy for determining the relevance of non-firm connection.

Assumptions related to slack node voltage for LV power flow analysis

A key parameter of LV-level power flow analysis is the upstream MV-level voltage, that serves as the reference "slack node" voltage. We used two different values for this parameter:

- the first option is to use the upstream voltage value that results from an MV-level power flow analysis. Using this value will tell us how much power we can connect to the LV grid today, in the current state of the MV and LV grid. We call this a "type T" (as in "today") power flow analysis.
- The second option, which was the one used by the DSO for their own connection studies, is to consider that the upstream voltage is equal to 105% of the nominal MV voltage - regardless of the actual voltage that can be reached on the MV network given its physical characteristics and loading conditions. The rationale behind this assumption is that the upstream MV voltage may vary later, so that LV connection studies should be performed based on the highest possible voltage that may be reached in the future; not on

the highest voltage that can be reached today. As a consequence, the DSO commits to keep the MV voltage below 105% of the nominal voltage, and then uses this value as a basis for LV-level power flow analysis. We call this a "type W" (as in "worst future case") power flow analysis.

In effect, using the first of these two values in the context of a non-firm connection study tells us how much energy we would need to curtail today, and using the second value tells us how much energy we may need to curtail in the future at worst.

Assumptions related to slack node voltage for MV power flow analysis

Similarly, MV-level power flow analysis requires making an assumption regarding the value of voltage at the secondary side of HV/MV transformers. These transformers are equipped with an on-load tap changer. The setpoint of this voltage regulator is chosen by the DSO. In France, this is done within the interval of 102% to 104% of the nominal MV voltage. Then the on-load tap changer strives to keep voltage equal to the setpoint. In France, DSOs usually consider that the voltage regulation mechanism has a 1% accuracy; in other words, if for instance the setpoint is 104% of the nominal voltage, then the actual voltage at the secondary side of the HV/MV substation will continually vary between 103% and 105% of the nominal voltage. Having no better information about the statistics of the voltage value within that ±1% interval, we considered that the voltage was randomly distributed within this interval, following a Gaussian distribution with 1% standard deviation that we clipped at ±1%. In other words, in our example above, we randomly drew at each time step the value of the "slack node" voltage within the [103% - 105%] interval. We applied this assumption both to "type T" and "type W" non-firm connection studies.

Modelling of power curtailment

From the operational viewpoint, non-firm connections may be implemented in different ways ranging from very simple to relatively complex. The simplest implementation consists in local control at the inverter level, based on local voltage measurements [2]. Complex implementations, sometimes referred to as "ANM" for "active network management" [3], may involve multiple sensors and multiple flexible generators, communication, state estimation, and advanced decision-making algorithms based for instance on optimization techniques to determine the curtailment level of each generator. Generally speaking: the more complex the implementation, the more complex the modelling. In our case, the situations under study were simple, with a single flexible generator and a single potential grid constraint that was systematically an overvoltage constraint located at the new generator's connection point. As a consequence, a simple implementation based on local control would suffice in practice. We thus decided to model the flexibility of each new generator by considering a local control as depicted on Figure 1.

As mentioned above, we always considered the new generator to be three-phase, even for smaller units that could apply for single-phase connection; and we modelled each three-phase generator as three identical single-phase generators that each independently apply the controls shown on Figure 1. In other words, we did not consider tactics that exploit network unbalance to limit curtailment; such as reducing power injection on one phase where the voltage is too high, while equally increasing power injection on the other two phases where the voltage is acceptable.

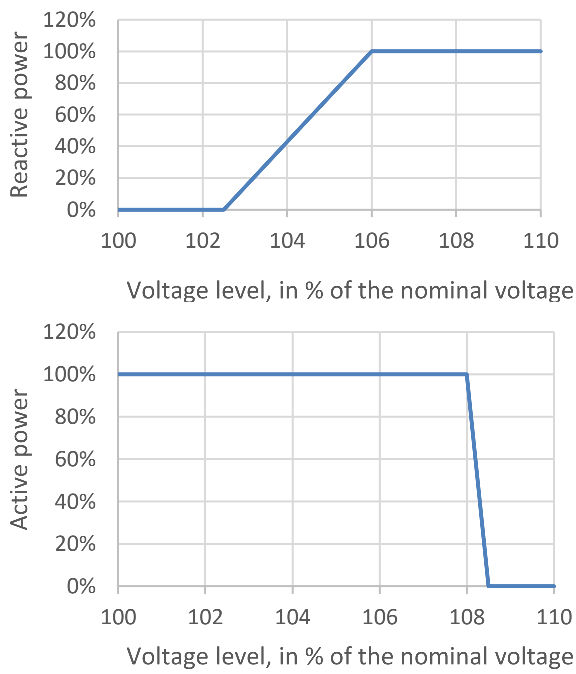
The rationale behind the control shown on Figure 1 is that, whenever voltage increases and gets close to the upper limit, we first act on reactive power, which does not incur loss-of-gain for the producer; and then turn to active power curtailment as a last resort.

This control logic requires specifying what capability the inverter has for reactive power management. We made the following simplifying assumptions:

- the rated power of the inverter is equal to the peak power of the PV unit, that was indicated by the connection applicant. This assumption was made for simplicity, in particular because detailed inverter data was not available.
- Whenever the Q(U) and P(U) controls shown on Figure 1 conflict, that is to say, when they lead to an apparent power that exceeds the rated power of the inverter, priority is given to the P(U) control: active power is curtailed as intended, and less reactive power than intended is consumed.

In other words, for simplicity, we did not investigate tactics such as deliberately increasing the rated power of

Figure 1: Q(U) and P(U) controls



the inverter for the sake of increasing its reactive power management capabilities (or conversely, reducing the size of the inverter for the sake of economy, at the expense of larger energy curtailment).

METHODOLOGY

Preliminary screening: completeness, consistency and reproducibility

For each case, we first checked the following criteria.

- Completeness and consistency of the available data.
- Reproducibility of the DSO's assessment: does the load flow analysis performed by the Local Authority confirm that (firmly) connecting the new generator to the existing grid would create a grid constraint? Which type of constraints (current or voltage) and where in the network?

Cases for which the data was incomplete or inconsistent were set aside. Similarly, we decided to eliminate cases for which our analysis, that we carried out by following as closely as possible the DSO's standard methodology, indicated that the network was constrained before connecting the new generator; or would not be constrained after (firmly) connecting the new generator. Such cases require comparative analysis to understand the reasons for the discrepancy between the DSO's assessment and the Local Authority's. A tentative explanation is that the DSO and the Local Authority came to very different estimates of the loading of the network, either in terms of peak power or in terms of distribution of the power along the LV lines. The distribution of power across the three phases may also have a strong impact on the outcome of the study. Indeed, the connection phase of single-phase customers (and almost all customers already connected to the grid were single-phase) is unknown, and yet has to be somehow taken into account in the study because most of the considered LV networks only feed a handful of customers, cf Table 1; the effect of voltage unbalance thus cannot be neglected. How exactly the DSO accounts for voltage unbalance is however unknown to the Local Authority, which may also lead to discrepancies between the assessments made on each side. Either way, the DSO and the Local Authority did not engage into this type of comparative analysis, and we simply set aside the questionable cases.

Coarse analysis

The load flow analysis that we performed at this step also yielded the following basic indicators:

- the (firm) hosting capacity MIN which we computed by running a power flow analysis on the network with minimum consumption while legacy generators, if any, are at 100% capacity. By definition, MIN is a lower bound for the maximum power that can be injected by the new generator at any time step without creating a grid constraint. The value of MIN can be computed both for "type T" and "type W" studies, the latter being the DSO's standard practice when processing (firm) connection studies.
- We also computed the "hosting incapacity" MAX by running a power flow analysis on the network with peak consumption; while legacy generators, if any, are at 0% capacity. This (unusual) loading situation provides an upper bound for the maximum power that can be injected by the new generator at any time step without creating a grid constraint.

We end up with three values WMIN (for "Type W", MIN),

Table 1

#	PEAK POWER (KWP)	NB OF CONSUMERS ON THE LV FEEDER	NB OF PRODUCERS ON THE LV FEEDER	LEGACY LOAD (KW)	LEGACY INJECTION (KW)	MV SETPOINT (% of nominal voltage)	MV MAX VOLTAGE RISE (% of nominal voltage)	WMIN (KW)	TMIN (KW)	TMAX (KW)
1	8.2	12	4	34	35	102	+0.1	0	35	100
2	8.2	3	1	4	3	102	+0.1	0	21	30
3	36	12	4	34	35	102	+0.1	0	29	85
4	36	3	0	9	0	102	-0.1	6	18	22
5	36	3	1	18	13	102	+0.2	0	44	56
6	15	15	1	29	6	102	+1.1	7	23	29
7	36	10	2	40	28	102	+0.9	0	9	48
8	33	5	1	10	6	102	+0.9	22	71	80
9	9	3	1	12	4	102	+0.4	2	29	54
10	99	1	0	3	0	103	+0.7	20	29	46
11	60	9	1	27	4	103	+0.2	27	53	77
12	98	1	0	40	0	102	+0.4	80	209	240
13	32	22	0	52	0	102	+0.5	11	26	43
14	80	0	0	0	0	102	-0.1	52	157	157

TMIN ("Type T", MIN) and TMAX ("Type T", MAX) as illustrated in Table 1. In case #3 for instance, the applicant wants to connect a 36 kWp generator, on a grid that can host between 29 and 85 kW today given the current state of the upstream MV network; and that would not be able to host any extra generation if the conditions on the upstream MV network changed for the worst. This simple analysis shows whether the new generator seems to create a "mild" constraint on the network or not, and thus whether it may be favourable (e.g. cases 6, 8 or 14) or not (e.g. cases 4 or 7) for non-firm connection.

Detailed analysis

We then performed a more detailed analysis by running of three-phase unbalanced power flow calculations over one year by hourly time steps, including the new generator equipped with reactive and active power control. We both ran "Type T" and "Type W" studies. The results are gathered in Table 2.

These results show, in particular, that in all cases except one, a non-firm connection would be relevant (in the sense of the criteria set by Order of July 12th 2021) in today's situation. However, when the worst possible future situation is considered, non-firm connections remain relevant only in two of our fourteen cases. These results raise the question of how likely the worst-case scenario is to materialize in practice; and suggest that non-firm connections could often be used as a "standby" solution, with grid reinforcement being deferred until it actually becomes necessary. It would then be possible to carry out a cost-benefit analysis taking into account the avoided grid works (when the worst case never materializes) and the discounted cost of the deferred grid works (when the worst case does eventually materialize). This additional analysis would thus require a long-term forecast of the future evolution of load and generation in the area understudy.

Table 2

#	*Type-T study*		Type-W study	
	Curtailed energy	Curtailed power	Curtailed energy	Curtailed power
1	0%	4%	9%	45%
2	0%	5%	12%	48%
3	2%	18%	15%	54%
4	1%	11%	25%	49%
5	1%	13%	24%	57%
6	0%	5%	8%	28%
7	1%	14%	14%	50%
8	1%	23%	38%	78%
9	0%	4%	11%	51%
10	7%	29%	12%	37%
11	1%	14%	9%	41%
12	1%	14%	10%	48%
13	0%	7%	4%	24%
14	0%	1%	3%	18%

CONCLUSION AND PERSPECTIVES

In the introduction of this paper, we raised the important question of whether non-firm LV grid connections would actually be frequently relevant in practice.
Our results suggest that, with today's grid, the answer may be positive However, in some cases, grid reinforcement might only be deferred and not avoided altogether.
The following final comments are also important to put our results into perspective.
Firstly, we only studied a limited number of projects, all from the same geographical area, so that additional investigation is needed before extrapolating the results.
Secondly, because the necessary data is not public, we were not able to quantify the frequency of the situation where generation projects are abandoned due to prohibitive connection costs.
Thirdly, as shown in Table 1, the voltage setpoints that are used in the studied area for HV/MV on-load tap changers, are relatively low compared with the allowed interval of 102-104%; then no substantial voltage rise occurs along MV feeders. This situation is very beneficial for non-firm connections in "Type T" situations, and results might differ in areas where MV voltage is higher.
Fourthly, recall that the voltage rise in the "last cable" was assumed to be equal to the 1.5% margin that French DSOs usually reserve for that purpose. Considering the actual voltage rise, based on the physical characteristics of the cables, may improve the benefits of non-firm connections.

For the time being, the French law mandates non-firm connections, yet does not explicitly state the methodology that should govern non-firm connections studies. Our results suggest that, if "worst-case" studies are used like they are for firm connection studies, then non-firm connections might be often discarded; while they might be much more widely selected when taking into account the benefits associated with cases where the worst case does not materialize, or only materializes after several years.

REFERENCES

[1] A. Hamdan, F. Cadoux, 2023, "Non-firm connections of PV generators in the low-voltage grid", *Proceedings CIRED conference*, AIM [Submitted for publication]

[2] M. Bernier, A. Coutarel, J. L. Geoffroy, 2017, "SMAP project or how to integrate crowdfunded DER in a rural distribution grid", *Proceedings of the 24th CIRED conference*, Open Access Proc. J., Vol. 2017, Iss. 1, pp. 1980–1983.

[3] L. Kane and G. W. Ault, 2015, "Evaluation of Wind Power Curtailment in Active Network Management Schemes", *IEEE Transactions on Power Systems*. vol. 30, no. 2, pp. 672-679