AMI-BASED NON-FIRM LV GRID CONNECTION FOR PV GENERATORS: FIRST REAL-WORLD EXPERIMENTS

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Keywords: PHOTOVOLTAICS, LOW-VOLTAGE GRID, FLEXIBILITY, SMART METERING

Abstract

Flexibility is crucial for enhancing electrical network performance, managing costs, and integrating decentralized generation, such as PV systems, EVs, and heat pumps. However, effectively implementing flexibility, particularly at the local level for low-voltage (LV) networks, presents significant challenges. This study builds on prior research into using advanced metering infrastructure (AMI) to facilitate non-firm grid connections in LV grids. Earlier work focused on developing a software solution to manage LV-level overvoltages and overloads by controlling PV generators through the AMI, requiring only a simple local communication gateway between the smart meter and the inverter as additional hardware. This solution was initially demonstrated in a laboratory setting on a reduced scale. In this article, we report on new field experiments aimed at validating the technology in real networks. These experiments revealed new challenges, including power-line communication (PLC) issues, sometimes correlated with peak PV generation hours. Such problems were not observed in small-scale lab tests but became prevalent in larger-scale trials. Additionally, the study identified other issues, including non-technical challenges like acceptability concerns among producers whose generators were controlled, potentially impacting the adoption of non-firm connections. These findings highlight necessary improvements to AMI-based flexibility mechanisms, addressing both technical barriers and stakeholder concerns.

1 Introduction

1.1 Non-Firm Grid Connections for PV Generators

Non-firm grid connections are a specific type of contractual agreement between the DSO (Distribution System Operator) and one of its customers, under which the DSO has the right to occasionally curtail the customer's power consumption or injection whenever this action is required to prevent the power distribution grid from being congested. The rationale of this type of agreement is that it may allow the DSO to connect a new customer to an existing grid, without reinforcing it, in situations where a standard (firm) connection would have required grid work. In other words, non-firm grid connections allow the customer to obtain faster and cheaper connection to the grid, in exchange for occasional power curtailment.

Non-firm grid connections are especially useful when the grid connection cost, under a standard (firm) connection, would be prohibitive and lead to cancellation of the project. Also, non-firm grid connections are particularly well suited for the connection of generators (as opposed to loads), because curtailment is usually much easier to implement and much more transparent for generation units.

The typical use-case for non-firm connection is thus the following: an opportunity to build e.g. a photovoltaic (PV) generator is identified; the DSO conducts a (firm) connection study and concludes that grid reinforcement is necessary; the producer realises that the grid connection cost is too high for the project to be economically viable; and instead of abandoning the project, which is the usual outcome of such situations, the generator is built, connected to the existing grid without reinforcement, and enrolled into a non-firm connection agreement.

1.2 MV versus LV Non-Firm Connections

The scenario above actually exists today in some countries, including France, for generators with a capacity in the range of a few MW. Such generators are tied to the medium voltage (MV) grid. On a technical level, this means that the DSO can rely on its existing SCADA system to operate the non-firm connection, that is to say to detect congestion, send curtailment setpoints, etc. Targeting larger generators is also appealing because each flexibility contract will provide the DSO more curtailment capacity, hence will potentially avoid larger reinforcement costs, than a contract with a smaller generator would. For all those reasons, DSOs currently tend to deploy non-firm connections very selectively, for a handful of specific cases involving large MV-tied generators. At the low voltage (LV) level on the other hand, where generators are plentiful and offer low curtailment capacity individually, where economic stakes are lower, and where no SCADA system is available, non-firm connections are usually not currently implemented by

DSOs. Non-firm grid connections are thus an untapped potential solution to increase the hosting capacity of low voltage grids, especially for generators.

1.3 Leveraging the AMI to Support Non-Firm Connections

To overcome the obstacles that are currently hindering the deployment of non-firm grid connections by Distribution System Operators at the LV level, we argue that a key element is to leverage the existing smart metering infrastructure or AMI ("Advanced Metering Infrastructure"). The rationale of this choice is to make non-firm grid connections as economically efficient as possible by relying on existing assets rather than investing in a dedicated infrastructure for the monitoring and control of non-firm generators. This idea parallels what DSOs are currently doing at the MV level when they reuse their existing SCADA system to implement non-firm grid connections for MV generators.

In the context of French LV networks, we thus advocate the general control architecture depicted in Figure 1.

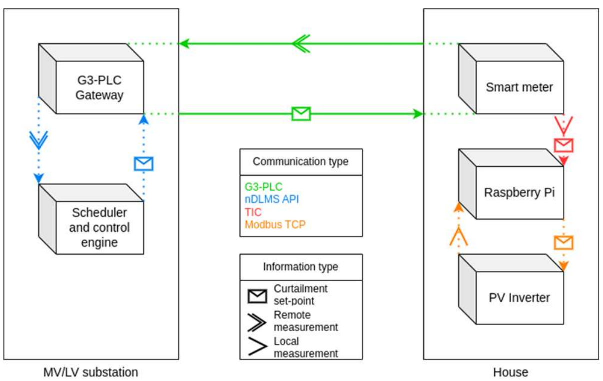


Fig. 1 Proposed Control Architecture

In this architecture, the Main Controller (scheduler and control engine in Fig. 1) is a software component that runs inside the data concentrator at the MV/LV substation. Its role is to consolidate readings from smart meters; to estimate the state of the network and the risk of undergoing congestion; and to compute curtailment setpoints if necessary. Those setpoints are then sent by G3-PLC to smart meters that pass them forward to the photovoltaic inverter through a home-area communication gateway. In our experiments, the home-area gateway was simply a Raspberry Pi microcomputer using two wired communication interfaces, one with the smart meter (using the French "Télé-Information-Client" or TIC protocol) and the other with the PV inverter (using the Modbus protocol). In top of the Main Controller, which is centralized, a decentralized Volt-Watt Local Controller is implemented at the home-area level to supplement the slower centralized controller.

The counterpart of this design choice is the necessity to cope with the limitations of the AMI, an infrastructure that was not designed for real-time use, and imposes strong constraints in terms of metrology and telecommunications. The controller should thus be designed with these limitations in mind, and then carefully tested and validated to ensure that satisfactory control performance can be achieved without abusing the capabilities of the AMI.

1.4 Gradual Validation of the Controller

To validate the feasibility of our approach, we first developed an implementation of the software components depicted in Figure 1, as well as a reduced-scale laboratory setup composed of real hardware (smart meters, PV inverters, etc) that allowed us to run the controller in a controlled environment and assess its performance. This first batch of in-house lab experiments is described in [1].

To further validate the technology and increase its maturity level, it was then necessary to run more diverse and more realistic tests. This called for real-world pilot projects at the multi-kW scale, using standard solar inverters, real PV panels subject to changing weather conditions, and with the PLC communication being subject to real-world conditions such as long lines and electromagnetic noise. This paper presents the results of this new batch of experiments.

All of these experiments relied on the same smart metering equipment, namely standard French smart meters using G3-PLC and a G3-PLC gateway known as nBox-SG from the company Neuron AG.

2 SysTec experiments

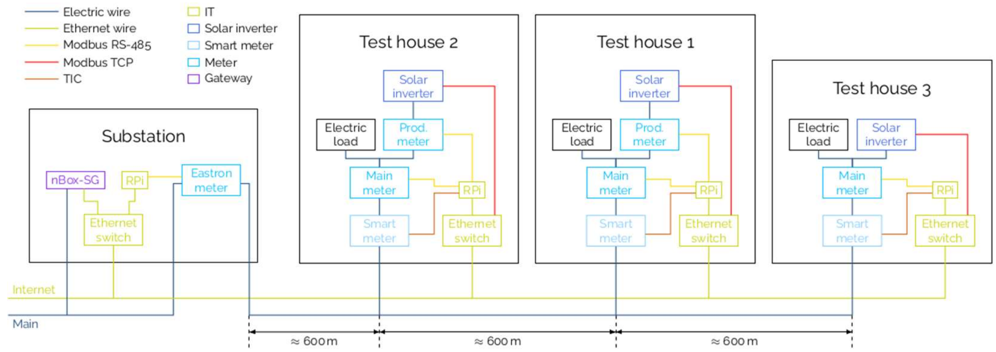
2.1 Setup Description

Fraunhofer IEE's SysTec test centre is a laboratory dedicated to conducting realistic tests on grid integration and connection of electric vehicles, renewable energy systems and storage technologies. The facility spans 80,000 m² and notably features a configurable low voltage grid feeding three small buildings. Although this infrastructure is not properly speaking a real-world grid, it is substantially more realistic than the laboratory setup that we had developed in-house, and was thus an appealing platform to further validate our controller. This was made possible thanks to the ERIGRID 2.0 program [2].

During the experiments at the SysTec facility, each one of three houses was equipped with a photovoltaic generator. Houses #1 and #2 had three-phase solar inverters rated at 5 kVA while house #3 had a three-phase inverter rated at 9 kVA. The largest inverter was located at the extremity of the network, as far as possible from the substation. Leveraging the versatility of the configurable LV grid, which offered LV cables of varying sizes and length, we used the longest and most impedant lines; these provisions ensured the occurrence of voltage violations. The test network is depicted in Figure 2.

Additional monitoring equipment (Janitza UMG-604 pro meters, Eastron SDM630MCT-ML) were used to measure

Fig. 2 Schematic of the grid used for the SysTec experiments



voltages, currents, and powers at every extremity of the network at a 15-second sampling rate. These additional measurement devices would normally not be available in practice and were thus not used as input for the controller; their sole purpose was to finely assess the performance of the controller, that is to say, its ability to avoid technical constraints while shedding the minimum amount of energy.

The experiments were conducted over a period of two non-consecutive weeks, in December 2022 and then in June 2023.

2.2 Key Results and Takeaways

The main issue that was met during the experiments was the occurrence of PLC communication problems. These problems were solved after identifying that their root cause was a specific PV inverter that was emitting strong electromagnetic noise in the PLC frequency band. This only occurred when the output of the inverter was high, i.e. during sunny hours. Conversely, the telecommunication problems disappeared during the periods of low PV output, i.e. during cloudy hours and at night. This inverter would thus not make the AMI entirely inoperative, especially if the communication between the concentrator and the smart meters was performed at night: it would still be possible to achieve the basic functionality of the AMI, i.e. to retrieve consumption data for billing purposes. However, this inverter would prevent the implementation of AMI-based control, since it blocks telecommunication during the exact periods where the control is the most needed (i.e. during sunny hours). It is unknown to us whether this particular inverter was faulty, or whether the behaviour would be the same for all units of this model of inverter, and maybe for other brands and models as well. For this reason, we could not draw general conclusions, but we gained the insight that the perturbation of the PLC channel by certain PV inverters may hinder the implementation of AMI-based control of PV generation.

Another takeaway of the SysTec experiment was the observation that the inverters available at SysTec reacted surprisingly slowly to control setpoints. Discussions with SysTec personnel revealed that this was caused by German regulation that restricts the rate of change of the inverter's output when PV inverters are subject to external control. Compared with our previous experiments, this made the controller less dynamic and reduced its performance. We thus gained the insight that such limits imposed on the rate of change of the power output of PV inverters could also have a detrimental effect on our control.

3 SOREA experiments

3.1 Setup Description

SOREA is a DSO located in the south-east of France. It serves ~14,000 customers. The pilot project was carried out on a LV grid that feeds a photovoltaic canopy with approximately 45 kW capacity.

The controller operated for about six months from September 2023 to February 2024. Due to this extended time frame, and to the fact that the site was located about 100 km away from our office, we equipped the controller with 4G connectivity and monitored it remotely.

3.2 Key Results and Takeaways

This experiment proved challenging for several reasons.

First, the same type of PLC communication issues that had been observed during the SysTec experiments surfaced again. This time, because we were operating on the real grid and did not own the generator, we were not able to experiment with shutting down or replacing certain inverters in an attempt to pinpoint PLC communication issues to a specific one. We were only able to implement a workaround, which was in itself a takeaway of the experiment: we found out that adding more smart meters to the network solved the telecommunication problem. Such additional meters act as repeaters in the PLC network (which is the reason why we attempted this subterfuge in the first place); this may explain why this solution did solve our PLC communication problems.

Another challenge that we faced in this experiment was that the generator, although quite powerful (45 kWp), actually had little impact on the local voltage; this was due to the fact that the generator was located very close to the MV/LV substation and that the upstream grid was quite strong. Consequently, it made no sense to control voltage using this inverter as the actuator; only use-cases where a current constraint is involved (e.g. overloading a distribution transformer) may be tested on such a generator.

4 Gervans experiments

4.1 Setup Description

The Régie SDED Erôme-Gervans is a local DSO serving a few hundreds of customers in the southeast of France. The site chosen for the experiment was a 9 kWp photovoltaic generator, connected to the grid via two single-phase inverters of 3.3 kVA each (for a total of 6.6 kVA). Because the producer had a single-phase subscription, both single phase inverters were connected to the same phase of the grid. The LV feeder did not feed any other generator.

This site was particularly relevant for experimenting with non-firm grid connections since the voltage did regularly reach the upper limit of 253 V (+10% of the nominal voltage) during sunny hours. In turn, this regularly caused the interface protection of the generator to trip. The large contribution of the generator to voltage rise was due to a combination of factors; the main ones were its single-phase nature, and the fact that the LV feeder was relatively long (~700 m) with a relatively weak neutral conductor (aluminum 70 mm², compared with 150 mm² on the phase conductors).

Another specificity of this experiment is that we were not allowed to curtail the generator, which we did not own; we thus resorted to adding a controllable resistive load of 2 kW (~30% of the capacity of the generator) next to the generator. The curtailment of the generator was then implemented not by controlling the inverter using its Modbus interface, but by activating the load. While it reduced the realism of the experiment, this design had an upside: it allowed us to measure the amount of shed energy, which is usually inaccessible when using direct inverter control.

4.2 Key Results and Takeaways

The experiment first showed that it is unfortunately easy to create constraints by connecting even small generators to the low-voltage network in rural areas: a PV generator of just 6.6 kW, which was connected to a recently built feeder using relatively robust conductors, at least for the phases (150 mm² aluminum), was enough to create a high-voltage constraint. In addition, we observed that these constraints had a substantial detrimental impact on the producer's revenue, due to frequent tripping of its interface connection. This led us to several observations which, although they are not directly related to the topic of non-firm connections, seemed valuable to us.

First, conducting a detailed and quantitative connection study requires grid data, modeling software and simulation expertise that may not be readily available to very small DSOs like the Régie SDED Erôme-Gervans; for this reason, potential constraints may be overlooked at the planning stage. This may translate into actual constraints in the field. Second, although the high-voltage constraint manifested frequently by tripping events of the interface protection, it had gone unnoticed before our experiment, probably for years. It would have been desirable for the inverter to log these events, and to transmit them to the owner of the generator. Note that the generator is already monitored by its owner via a smartphone interface, which displays basic information such as the amount of energy generated; tripping events, however, are unfortunately not displayed.

Another result of the Gervans experiment was that we faced problems again with PLC communication. This time, we attributed these problems to the long distance (700 m) between the secondary substation and the generator. In this experiment, we were not able to add additional smart meters to act as repeaters, and we did not manage to solve the telecommunication issues. We thus resorted to using the Local Controller only.

This experiment also led us to experience issues with the stability of the Local Controller. On the one hand, we observed that using a relatively conservative controller (e.g. a controller with a slower dynamic and with a milder slope in the Volt-Watt control) had non-negligible detrimental impact on the performance of the controller, as it would translate into higher shed energy. On the other hand, we observed that a more aggressive controller could exhibit unstable behavior, resulting in bad control performance as well. This observation echoes what we had observed during the SysTec experiments, using inverters with low ramp rates: the parameters of the Local Controller must be set with care to ensure good performance. This issue is not redhibitory as it may be solved on a case-by-case basis, typically by means of software simulation and trial-and-error. However, this means that this tuning step, which must be done specifically for each LV feeder and updated every time the characteristics of the feeder are modified, adds to the complexity of implementing LV-level non-firm connections. The alternative would be to always use conservative controller parameters to ensure stability, such as a mild slope in the Volt-Watt controller and a large open-loop time response, at the expense of less effective constraint mitigation and higher energy loss.

This experiment also revealed that enrolling producers in a non-firm scheme may prove challenging. A key concern was the amount of energy that would be shed, and the value of the induced loss-of-gain. Our setup using a separate controllable resistive load was accepted for the experiment as it made it possible to measure with accuracy how many kWh were dissipated by the experiment, which served as a basis to compensate the producer financially. This solution, however, would not be practical nor economical in the context of industrial deployment of non-firm connections. This led us to the observation that the best way to monitor the shed energy, when PV inverters are directly controlled, is likely to do it inside the MPPT algorithm; indeed, this algorithm constantly evaluates the shape of the IV curve of the PV modules, from which the position of the maximum power point can be determined. Adding this feature to PV inverters may help facilitate the adoption of non-firm schemes by producers.

Other concerns were raised by the producer as well, such as whether controlling the inverter may lead to reducing the lifetime of the equipment (inverter, PV modules), or result in the loss of its warranty. Such concerns also must be addressed when developing non-firm schemes.

5 Final observations

After running different pilot projects with a variety of PV inverter brands and models, we observed a lack of standardization in the way inverters can be controlled: for each test, we had to find and analyze the document of each specific inverter, and to implement its own specific software driver. This heterogeneity clearly hinders the development of non-firm schemes as it requires custom work and makes it difficult to develop a fully generic version of the home-area gateway. This issue would be multiplied if LV non-firm connections were generalized to other types of flexible devices, such as EV chargers, on top of PV inverters. It is also worth noting that a similar compatibility issue can arise between the smart meter and the home-area gateway. We did not encounter this problem during our experiments because we always used the same model of smart meter. However, compatibility issues would likely have emerged if we had experimented with other meter models.

The Home-Area Gateway also needs to be industrialized. This device needs to achieve the following tasks: perform home-area communication between the smart meter and the inverter; convert from one protocol to another (for instance, from the French "téléinformation-client (TIC)" protocol to Modbus); implement basic control logic (e.g. detect that the communication with the Main Controller has been lost and fall back to a more conservative decentralized control mode until PLC communication is restored); and log information for analysis purposes. Ideally, the gateway should also be cheap, which calls for mass production, and easy to install. Such a device currently does not exist off-the-shelf, another factor hampering the deployment of non-firm connections.

We also observed that the smart meters that are currently used in France lack some features that would facilitate the implementation of non-firm schemes. An obvious example is that no COSEM object has been provided to send control setpoints to behind-the-meter flexible devices; consequently, we had to use a workaround and inject the setpoint in another data field called the "Customer Message". Another improvement would be the option to get data from the flexible device and transmit it to the data concentrator (which is not feasible with the smart meters we used). This option would make it possible for the DSO to collect data such as the power output of the inverter, which is useful for control purposes and may not be measurable by the smart meter itself (since the PV generator may not be the only device behind the meter). If the amount of shed energy was measured by the inverter itself, as suggested above, it would also be useful both for control purposes, and to evaluate the economic impact (loss-of-gain) for the producer, to transmit it to the data concentrator.

Finally, note that the Main Controller, which is essentially an add-on to the firmware of the Data Concentrator of the G3 PLC network, must be integrated within its firmware. In some cases, the firmware of the Data Concentrator is owned and maintained by the DSO; in other cases, the DSO purchases a proprietary solution. Both cases coexist in France. In any case, close cooperation between the provider of the Main Controller and the provider of the Data Concentrator firmware is required; we observed that this could be a major practical difficulty.

6 Conclusion and perspectives

Realizing realistic implementations of AMI-based non-firm LV grid connections for PV generators proved both challenging and insightful. A key issue that appeared during field trials was the quality of PLC communication in general; and more specifically, the risk that this quality may be the lowest during the exact periods where communication is needed the most, namely, during sunny hours with strong PV generation. This topic requires more investigation and will be the topic of our future work. Our experiments also suggested several technical improvements that could be made to PV inverters and to the AMI infrastructure to facilitate the implementation of non-firm schemes. Finally, it highlighted the need for standardisation, and for addressing acceptability issues.

7 Acknowledgements

The authors wish to thank for their support: ADEME (Agence de la Transition Écologique), the French Agency for Ecological Transition; the ERIGrid 2.0 project; the Fraunhofer SysTec (System Technologies Development) Center; SOREA; and the Régie SDED Erôme-Gervans.

8 References

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