Micro storage and demand side management in distributed PV grid-connected installations

Conference Paper · November 2007

DOI: 10.1109/EPQU.2007.4424208 · Source: IEEE Xplore

9th International Conference. Electrical Power Quality and Utilisation. Barcelona, 9-11 October 2007

Micro storage and Demand Side Management in distributed PV grid-connected installations

Vallvé X., Graillot A., Gual S.
Trama Tecnoambiental S.L. (TTA)
Ripollès, 46 – 08026 Barcelona - Spain
tta@tramatecnoambiental.es

Colin, H.
CEA/INES-RDI
BP332, 50 avenue du Lac Léman
73377 Le Bourget du Lac - France
Herve.colin@cea.fr

Abstract— **The liberalisation of the electricity market, combined with the need to reduce CO2 emissions, lead to future electricity grids with a large fraction of distributed renewable energy generation. The dispatch of renewable distributed energy sources at present is performed in such a way that, when implemented at very large scale, their intermittency can impact on the grids, what leads to concerns in terms of power quality and of security of supply. The objective of this work is to analyse the benefits of a storage system in domestic PV (Photovoltaic) grid-connected installations. The paper explores how micro-storage could minimize some distribution problems for the end-user (micro cut-off, black-out) and could allow injection into the grid with dispatch strategies that combine deferred PV generation and demand-side management of domestic loads. The main objectives of this innovative concept can be summarised as:**

- **Study the distribution grid quality to get a picture for introduction of distributed generation devices**
- **Estimation of market potential for small distributed generation and grid stabilization systems in Europe**
- **Analysis of the typical load profiles in order to identify the consumption peaks**
- **Technical requirements for the system, including all its functionalities, especially for the grid interface and the storage system**
- **Demand side management strategies**

Keywords- PV generation, demand- side management, battery storage, continuity of supply.

I. Introduction

Presently, the integration of distributed renewable energy is performed in a so called "feed and forget" way. As its share in the electrical mix increases there may be concerns in terms of quality and of security of supply to the end users but also output energy loss if the dispatch strategy is not well adapted.

Based on some data this paper presents some overview about the quality of the networks within selected European areas. It then details the reciprocal interaction between PV electricity production and the low voltage grids. Then, some data is presented about the potential impact on the low voltage grid operation of PV systems on buildings that integrate a storage function.

Furthermore, the paper describes the different components of the system (size, type, etc) and the way of operation with a focus on the load management, which entire part of the system.

II. Quality of grids and impact of PV

With the steadily increasing penetration of distributed generation in electric power systems, Power Quality (PQ) and more generally the Security (without interruption) and Quality of Supply (SoS and QoS) are key issues which have recently gained increased attention and have been the subject of many studies during the last decade: customers as well as grid operators are well aware that secure and efficient operation of power distribution and customers' equipment is intimately connected with a high QoS level.

A. Quality of the networks

Disturbances in the voltage supply can cause tripping or even damage to sensible appliances. These disturbances include voltage sags, dips, transients, swells, harmonics as well as short interruptions. They are generally caused by weather, accidents or utility equipment failure.

The interruptions can range from only minor events lasting for few seconds to blackouts such as the ones experienced in the USA or in Italy only few years ago.

The frequency of occurrence of the “power-quality and reliability events” depends on the electrical system and the situation is heterogeneous in Europe. Today, power quality and reliability events are very scarce in strong and oversized grids, such as in Germany or France (except in over-seas territories), whereas they happen more often in weaker grids.

For example, the grids in UK or in Eastern Europe are facing an increasing number of power supply concerns. As an example, a study issued in April 2004 of the EU accession countries working group of the Energy Regulators Regional Association showed that planned and unplanned interruptions in supply could be as frequent as 9 times a year per customer with a number of minutes lost of as much as 332.

Reference data could be gathered in France and in Spain about the duration of power supply interruption for private homes.

In France, data was published for 2004 and 2005 about the duration of interruption of supply cumulated by customer for each department. A summary of this data is given in table I.

TABLE I. DURATION OF GRID INTERRUPTIONS IN FRANCE

	2004 Due to transmission level	2004 Due to distribution level	2005 Due to transmission level	2005 Due to distribution level
Average (min)	2	49	5	50
Max (min)	36	175	73	132

These figures are typical for strong grids and show that under “normal” operation, the interruption of supply are both seldom and relatively short lasting. This fact is confirmed by a more detailed case study in Spain.

For a case study in Spain, focusing on the continuity of supply, the requirements for quality are related to geographic zones, where the regulation defines the minimum levels of continuity of supply. (Table II).

TABLE II. NUMBER AND TOTAL DURATION OF INTERRUPTION PER YEAR IN THE DIFFERENT CATEGORIES OF ZONES

	Number of hours	Number of interruptions
Urban Zone	6	12
Semi-urban Zone	10	15
Concentrated Rural Zone	15	18
Scattered Rural Zone	20	24

The events taken into account for the calculation of the continuity of supply (number and total time of interruptions) are the ones which last more than 3 minutes.

The distribution companies join their effort in order to solve the incidents shorter than 3 minutes, realizing actions which minimize their impact and reduce the number of affected clients by installing on the distribution grid automatic devices that disconnect a part of the affected market.

It is relevant to study the duration of typical incidents for each zone, in order to determine the requirements of alternative supply systems during the interruptions. The results are shown in Table III.

TABLE III. INTERRUPTIONS IN DIFFERENT ZONES: CUMULATIVE VALUES (E.G: 93,9% OF THE INTERRUPTIONS LAST LESS THAN 240 MIN IN URBAN ZONES, OF WHICH 36,3% LAST FOR LESS THAN 60 MIN)

	3 min	60 min	120 min	180 min	240 min
Urban Zone	6,2 %	36,3 %	75,3 %	88,8 %	93,9 %
Semi-urban Zone	10,3 %	30,9 %	69,8 %	85,8 %	92,3 %
Concentrated Rural Zone	3,9 %	21,4 %	61,4 %	81,2 %	90,0 %
Scattered Rural Zone	4,9 %	21,0 %	55,9 %	76,4 %	87,0 %

We can see that if we were able to supply electricity during 3 hours (180 minutes), the impact of a large fraction of the incidents would be eliminated. Note that it is almost impossible to cover 100% of the incidents. As we can see in Figure 1, at around 90% of total interruption and duration in the range of 180 min, the slope of the curve changes drastically. This means that if we wanted to increase the fraction of the covered incidents, we would need to increase drastically the time of alternative supply.

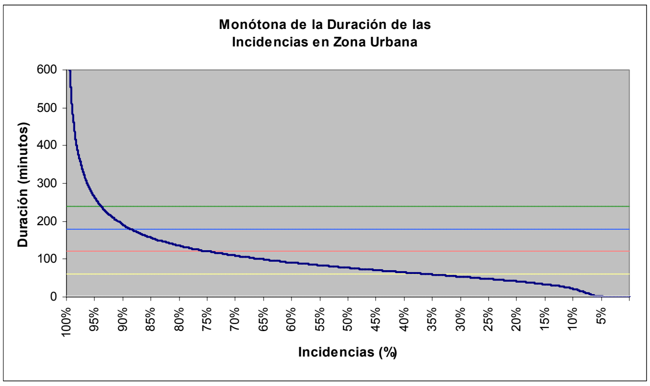

Figure 1. Duration of interruptions vs cummulative fraction in an urban zone in Spain.

As a conclusion, we can observe that a duration of up to 180 minutes of an alternative power supply is sufficient to neutralize the impact of most incidents.

B. Interaction of PV and grid

The interaction of the grid and the installed PV generators is reciprocity. In the following paragraphs, attention is given to both the impact of PV generators on the distribution grid as well as of the distribution grid on PV generators.

1) Impact of PV on the grid

The amount of PV systems and of PV production is increasing drastically in European countries as well as in Japan.

Only few studies exist on the monitoring of grids with increased penetration of PV. A first study was performed in the frame of the DGFACTS project by Arsenal Research that showed "that the decoupling protection, as a core component of every DG installation, deserves particular attention. Too sensitive settings or inappropriate design can not only lead to problems regarding the reliable operation of the plant but furthermore also be a source of power quality disturbances in the grid".

Interviews with utility specialists leaded to the conclusion that, for private installations, that are limited in their size by the surface of the roofs, the fluctuation of the power output of single installations is not an issue and will not be an issue in the future either. Therefore, from their point of view, PV private installations do not have any impact on the grids operational issues. This point may be more critical as many installations are concentrated in a same area with same climatic conditions.

Potentially, the impact of PV on the grid will be more sensitive with increasing impedance of the network at the integration point. This impedance at a given integration point depends of 3 variables:

- the distance between the point at which the impedance is calculated and the next power station
- the size of the transformer (it ranges from some kVA to 1MVA)
- the feeder cable length and cross section between transformer and user.

Finally, minimising the potential transients of PV installations can be easily performed by an adaptation of the inverter so that it injects the current following a ramp.

But if PV generation and the related transients do not impact on the grids operation and is not responsible for power quality events, a large penetration of PV can impact a lot on the grid planning.

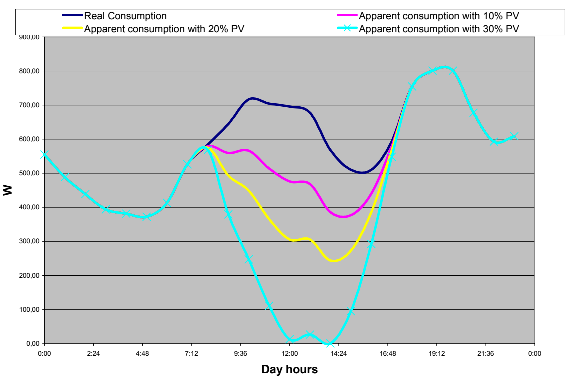

Figure 2. Real and apparent load profile, with 10 to 30% PV penetration in an average day.

The figure 2 shows a load profile representative of a mixed urban area with households and small businesses, during a typical winter day in Spain. The profile of the real consumption (data obtained as % of simultaneity of the MV-LV transformer) is represented as well as the simulation of the apparent load with 10, 20 and 30% PV penetration (in term of energy.

The first result that is significant from the simulation is that a penetration of 30% of PV in the energy mix in such an area is a maximum threshold when we have direct injection. Above this value, the transformer has to work in a reverse way and energy must be fed from the LV to the MV grid. There is risk of disconnection of PV caused by over-voltage and the net efficiency of DG is lower.

The second result is that PV energy fed directly is not able to smooth the load curve in such an area. Only the day peak disappears but not the evening peak.

These two observations are strong arguments in favour of what we have called SoS-PV system, i.e. a PV generator that integrates a storage function.

Hence, partial storage of PV energy during the day will:

- allow a higher penetration of PV energy;
- allow a smoothing of the load curve since electricity can be injected partly during the day peak and partly during the evening peak.

2) Impact of the grid on PV installations and on customers

The poor quality of a grid can have an impact on the loads of the end user, especially on sensitive loads. For this reason, many users install UPS devices that secure in particular their computers and other critical loads.

In addition, the poor quality or the interruption of power supply from the main grid impacts on the productivity of the grid-connected PV system that is connected to it, thus reducing sometimes noticeably its performance ratio. The curve in figure 3 is the example of the production of a PV system on the 15th of January 2006, in the south of France. The PV system is connected to a LV network, relatively far away from the last transformer and power station.

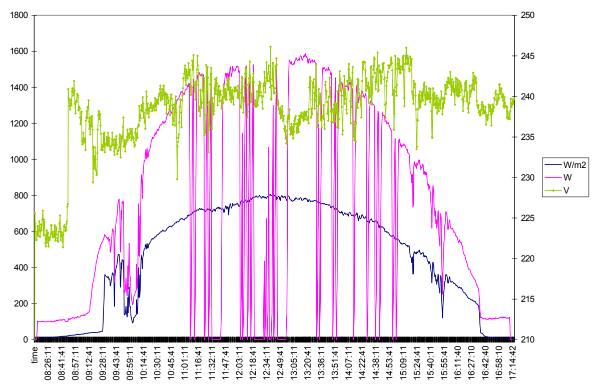

Figure 3. Irradiation, power fed to the grid and grid average voltage for a 2.6kW PV installation in France.

It can be observed that the production is only 77.5% of the expected production on that day. A more precise analysis of this behaviour shows that the disconnections occur in times than the grid voltage is high and that the disconnection is related to the reaching of the high voltage disconnection threshold. E.g. similar observation were also made in Germany: on a sunny Sunday, when no load is drawing power from the grid, the injection of PV current is leading to a rise in the voltage in "end of line" configurations and to subsequent disconnection of the PV system.

Therefore, in many cases, the grid has an impact on the PV systems in so far that their productivity can be decreased. As the inverter detects the quality of the signal, any perturbation on the grid disconnects the PV array and the energy production is stopped during this period. The perturbation can be an interruption or the bad quality of the current (voltage and frequency out of the range, etc). The PV generation and then injection on the grid can be strongly affected and the performance ratio can decrease up to 40% in cases where the injection point has high impedance.

Another factor which could affect the efficiency of the system is the time of reconnection. After an interruption, the PV system has to wait a certain period before the reconnection. Depending on the national legislation, the losses can be important, for example in Spain where the time of reconnection is 3 minutes.

III. Storage for Grid-Connected PV Systems

A. *Pertinence of storage*

There are three arguments in favour of the introduction of a storage function coupled to a grid connected PV microplant.

First, storage can improve the security of supply. One of the problems concerning the grid quality in Europe is the incidents which can cause a perturbation in the supply of energy to the users. Even in the best grids, such events can occur, and in most of the European countries, the short or long interruptions are quite common. At present, a user with a grid-connected PV system could stay without electricity during daytime if there is an interruption of the grid service. Considering that he has a PV system generating on his roof, such a user is suffering a big contradiction.

The observations about the interruptions showed that the storage should ensure a total of 3 hours of autonomy for the users, which will allow the system to cover 90% of the interruptions.

Second, the addition of a storage function can also increase the global performance ratio of a PV generator either by hindering over-voltage disconnection or by storing the energy produced during the disconnection time and feeding it in the grid after reconnection.

Finally, a large penetration of PV will not be able to cover all consumption peaks. Therefore, storage seems necessary to deferr the energy injection to the grid during the peaks of load which do not correspond to the peaks of PV generation. In the case of a high PV penetration in the Low Voltage distribution grid, the impact will not be negligible and the interest for the utility can be quite important for the injection of energy on the grid when it does need it.

The following figure 4 presents the load profiler consumed during different days of the year in France.

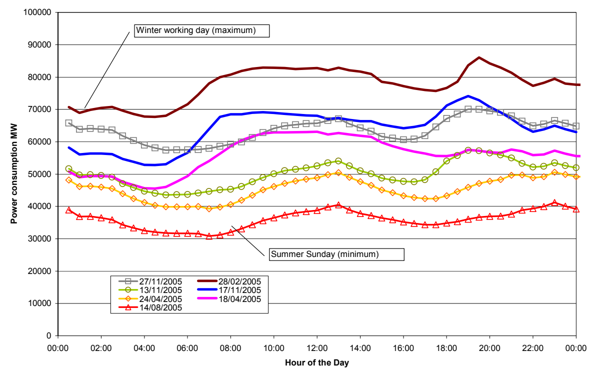

Figure 4. Load profile in France during different days of the year 2005 (data RTE) (Bold lines = working days, thin lines with marks = Sundays)

Clearly, the consumption peak of the day can be partly covered by PV generation while the evening peak, that is even higher than the daylight peak, cannot if no storage is available.

Figure 5 represents the load profile simulation as a power delivered by a sub-station for the two scenarios in an urban area in Spain:

- in one case PV is fed directly to the grid
- in the second case, PV is fed directly during peak hours and stored in the battery during the rest of the day in order to be fed during the evening peak.

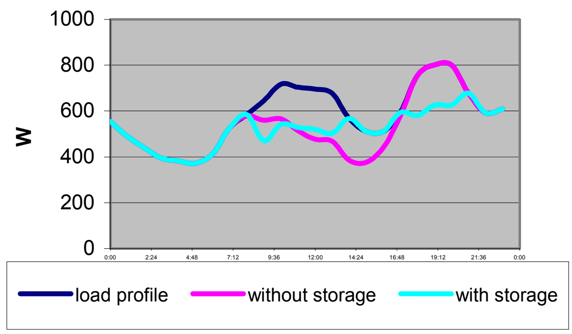

Figure 5. Load profile of an urban LV network during normal operation, with 10% PV penetration and with PV and storage

Nevertheless, the scenario of energy shifting is not applicable right now due to the low penetration of PV and to the fact that constant feed-in tariffs do not motivate PV system owner to inject at peak hours.

B. *Considerations about the sizing of the system components*

The following sections attempt to give an order of magnitude of the different components of the system.

1) *Considerations about the PV array sizing*

Sizing depends basically on the following criteria:

- the general requirements for the SoS-PV system,
- the energy demand,
- the solar radiation,
- the feed-in tariffs in each country.

Focusing on the feed-in tariff, it is possible to formulate hypothesis about the upper and lower limits for the PV size.

With a high feed-in tariff, the PV size will be as big as possible depending on the economic capacity of the investor. The lower desirable limit for the PV size will be the equality between the energy generation and the energy consumption of the user.

With a non-incentive feed-in tariff, generating and selling a lot of electricity is not economically valuable. The upper limit for the PV size will be the equality between the energy generation and the energy consumption of the user.

Even if the feed-in tariffs are guaranteed for many years in most of the European countries, it is also realistic to imagine that this incentive measure will decrease and could disappear in a long-term (20-25 years). While, in a liberalized market the cost of electricity will vary along the day according to the demand.

As a conclusion, the first hypothesis for the sizing of the PV array is to consider that the electricity generation will be equal to the electricity consumption, which is the case of Spain will represent a PV array of around 4.5-5 kWp.

2) *Considerations about the inverter sizing*

In non dispatchable PV generators, the size of the inverter is similar to that of the PV array.

During its operation, the inverter reaches its rated power only in very few occasions. Most of the time, it works at a lower power level, where the efficiency is somewhat lower. This over sizing results in increased cost.

In the SoS PV configuration another alternative has to be mentioned, based on relevant observations. With storage, it is possible to undersize the inverter and to use the storage system to absorb the peaks of power generation. The advantage is triple:

- it is possible to have an agreement with the utility to dispatch the accumulated electricity during the optimum time hours
- the cost of the inverter is lower
- the global efficiency of the inverter is the high during most of the operation

The first argument is of course the one that should be leading to the largest economical benefit.

Upper size limit:

One limit for the inverter size is the threshold between single and three phases. One requirement for the system is that the inverter works in a single phase. According to the regulations around Europe, this average threshold is fixed at 4.5-5 kW. Therefore the inverter should be smaller than 5 kW.

Lower size limit:

In case of cut-off of the grid, the PV energy (direct or through battery) will assure the supply to the electric consumptions. During this period, it is assumed that only the critical louds will be covered. According to previous studies, we can say that the basic power level required to cover them is around 1000-1200W. This defines the lower size limit for the inverter. In this respect, the calculation bases on a study of the critical loads that must be supplied during an interruption on the grid. The load that will need most power in the house is the fridge, which nominal power is in the range of 150W for a class A product. Measurements of the peak load current for starting the compressor in the worst case is in the range of 10 times the nominal power. Therefore, an inverter in the range of 1500 W able to deliver 30% overload for a short time would be sufficient for securing the critical loads.

The exact size of the inverter will be determined by the daily energy that will be injected in the grid.

A simulation based on the case of Spain lead us to define two grid scenarios which are:

- residential
- mixed (residences, shops, services, SME...)

The inverter must have a power size which allows the system to inject on the grid all the electricity generated daily by the PV array.

Based on the scenario with the highest value of energy flow, we can conclude that on reference for the inverter size will be:

Inverter nominal power = 1540 W

This value is calculated by dividing the total amount of energy that is produced by the PV array within one day by the number of hours the grid will ask for support.

Finally, we can introduce the notion of modular inverter. If we consider several levels of consumptions, the combination of two or three inverter may be possible. The idea is that the power size will be such as we could combine as many inverters as possible without exceeding 4.6 kW (lower threshold single 3-phases) to respect the monophasic regulation, in this case 3.

Inverter power size = 4.6 / 3 = 1530 W

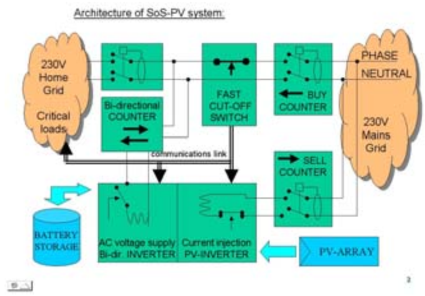

Figure 6. Architecture of SoS-PV system

3) Operation of the system

The functional description of the system in each configuration can be summarised as follows:

- Grid with normal supply
- Operation of the system in case of grid cut-off
- Return to the initial conditions
- Battery charging

In all the modes of operation it is important to state that the load management is implemented according to the state of system: dispatchable loads, switch of certain loads, etc.

a) Grid with normal supply

Normal operating mode of a grid connected photovoltaic inverter, with improved features.

The PV system works independently of the grid supply. Therefore, if there is solar radiation, we will charge the battery or maintain the floating level and injecting the difference into the grid through a specific independent meter.

The energy generated will be injected into the grid according to the utility needs, that is to say during the peak of consumption. According to the situation (type of needs in the distribution low voltage network, season, etc), the system will inject directly the energy generated by the PV array or the energy stored in the batteries, if the peaks do not correspond to the PV generation.

It is important to foresee a 'reserved stock' in the battery in case of interruption of grid supply, since the storage system has to assume the supply of the basic needs during this period.

b) Operation of the system in case of cut-off of the grid

In case of interruption of supply, the following cases have to be pointed out:

- Micro-cut
- Long Interruption

The strategy for each situation is described as following.

Micro-cut

It is called 'micro-cut' an interruption of the supply inferior 50 milliseconds. This kind of interruption is due to by storms, wind, branches and trees. These problems can be solved by using active or passive power line filter; no disconnection system is required in this case.

Long Interruption

A long interruption is an interruption which lasts more than one second. It can be caused by failure or maintenance works on the grid.

As we mentioned previously, the strategy, when short and long term interruption occurs, is the supply of the critical loads from the storage system and via the inverter, acting as an off-line UPS equipment.

c) Return to the initial conditions

Once the interruption is over, the system can restart the injection into the grid. In the case when the legislation requires a determined period before restarting the injection, the energy possibly generated by PV can be stored in the batteries.

d) Battery charging

After having supplied energy in case of interruption, this energy must be returned, that is: the batteries need to be recharged from the grid side, without compromising the normal PV energy injection into the grid. It is important to take into account the fact that the charging is quite long due to the fact that the charging current is lower than the nominal current of consumption.

The normal grid operation mode as reached once the energy supplied is restored to the battery.

IV. Conclusion

The present paper deals with the interest of a storage system in the PV grid-connected installations in order to address the different problems encountered in the low voltage distribution grids.

The study of grids quality shows that many grids around the world present weaknesses that are meant to increase as the power demand increases. The use of decentralised electricity production and in particular of PV energy can relax a bit the constraint on the existing networks but the present study showed that PV production peaks and demand peak are not always concomitant. Therefore, storage will be needed in order to defer the time of grid injection.

In addition, PV plants can impact the quality of the low voltage networks but moreover, the poor quality of a network will decrease the performance ratio of a PV system by as much as 40%. The use of a storage system will decrease the impact of a PV plant on the network and maximise the performance ratio of a PV system.

On the long term, the optimisation of a PV system with a storage function will allow the utility to manage its network so that PV injection happens only in high demand periods. For such configurations, using data corresponding to the Spanish situation, it could be calculated that a system with 2.2 kWp and an inverter size of 1.5 kW would allow injecting all along the year during 3 to 9.5 hours when the demand is 15% over the average of the day.

References

[1] Kristina Hamachi, LaCommare and Joseph H. Eto, "Understanding the cost of power interruptions to U.S. Electricity Consumers. September 2004.

[2] Shawn McNulty, (Primen) and Bill Howe (EPRI PEAC), "Analysis of the Prospects for Renewable PQ Solutions in Massachusetts, report on Power Quality Problems and Renewable Energy Solutions", Submitted to: Massachusetts Renewable Energy Trust September 2002.

[3] ERRA, EU accession Countries Working Group, "Quality of Electricity Supply – Comparative Survey", April 2004.

[4] Report IEA PVPS T5-04:2001: "PV System Installation and Grid-Interconnection Guidelines in Selected IEA countries".

[5] "Renewable energy: Market & Policy Trends in IEA Countries".

[6] B. Bletterie; M. Heidenreich. "Impact of large photovoltaic penetration quality of supply. A case study at a photovoltaic noise barrier in Austria".

[7] Catalogue Général SOCOMEC, Cahier technique sur la distribution B.