BESS Application to Mitigate the Fluctuations in Grid-Tied Utility-Scale PV Plants

Carlos David Liquet

Department of Sustainable Engineering – INATECH, University of Freiburg and Fraunhofer Institute

Abstract- Renewable energy sources such as photovoltaics may offer many advantages over conventional power generation sources, especially an abundance in supply of the energy source; however, the intermittence or short-term variability, especially, in utility-scale photovoltaic plants is a key drawback. Fluctuations in the output power because of incoming radiation variability is getting concern due to the negative effects on the power quality and reliability. The generation of electricity needs to match the demand, then the power fluctuations need to be compensated by another source to ensure matching. Since traditional dispatchable resources have limitation in responding quickly, PV generator need to be combined with any energy storage technology to reduce the fluctuations. This research provides an overview of the source of fluctuations in utility-scale photovoltaic plants and how to mitigate them by limiting the ramp rate of the output power through the usage of BESS.

Keywords*- Battery, controller, PV, ramp rate, smoothing.*

I. Introduction

Photovoltaic (PV) energy sector continues with a solid growth during the last years (IRENA, 2022) [1], some aspects that have contribute with this growth are the cost reduction on PV modules, the increase in efficiency, the incentive policies, the decarbonization process among others. Also, due to price-competitive, utility-scale PV power plants are a good solution to generate clean energy in large quantities [2], increasing in this way the renewable energy penetration on the grid. With "*penetration*" we mean the ratio of PV capacity to the total generation capacity on the utility system [3]. However, with the growth of PV penetration also come instability to the grid in term of power quality and reliability due to the variability that characterize this kind of energy [4].

To maintain the grid stability the generation-load balance process must be continually met, and when a large PV source significantly increases or decreases, another resource or demand change must compensate to ensure matching. Traditional dispatchable energy resources (nuclear, coal, natural gas, etc.) have limitation to respond quickly, thus fluctuations in PV due to transient cloud become an issue [5]. To overcome this problem, a combination of PV plus energy storage systems to either add or subtract power to or from PV output power is used in other to smooth out the power ramp rate injected to the grid [4].

Different energy storage technologies have been analyzed and proposed to mitigate the fluctuation in utility-scale PV plants [4]; however, we will limit our scope to the battery energy storage systems (BESS) since they have been growing rapidly due to technological improvements and reduced cost [6]. Their importance has grown in the last years due to the increased penetration of distributed generation and its application in the grid to provide ancillary services like voltage support, frequency regulation, transmission congestion relief, peak shaving and other ancillary services [6].

For PV smoothing or ramp rate mitigation applications, the primary question addressed is: how much storage is needed. To answer this question different approaches, techniques and methodologies are proposed in the literature [4], also nowadays the modeling tools available facilitate the analysis process. The ramp rate controller to smooth the fluctuations is another point of attention in this kind of application, it can be simple by only sensing the PV output power of the plant and the battery state of charge (SoC) but it could be even more complex by including also forecasting of at least 30 minutes to reduce the BESS size.

The aim of this research is to provide an overview about the source of fluctuations in utility-scale PV plants, how to analyze those fluctuations, also call ramp rate, by using an event as case study. Finally, we will provide an example of a utility-scale PV plant to model its output power and add BESS to limit the ramp rate.

II. Fluctuation in Solar Radiation Due to Transient Clouds

Short-term variability of solar radiation and its influence on PV systems connected to the utility grid have been analyzed from 35 years ago [3] and is attracting more attention now as the PV penetration increases. Some research have been carry out in different places around the world to analyze the variability of solar radiation at different time resolution, in [7], for instance, the distribution of incoming solar radiation at Fraunhofer-Institute of Solar Energy (ISE) in Freiburg (Germany) and at Solar Energy Research Laboratory (LABSOLAR) in Florianopolis (Brazil) were studied. Thought this research was carried out to determine the correct sizing of PV plants in term of the resolution of solar radiation, the data collected register short-term variability in cloudy days and its effect in the incoming radiation. At ISE the sampling rate used to capture the incoming radiation was 10 s and calculated at 1-min and hourly averages. At LABSOLAR 1-min data were captured and calculated hourly averages. Fig. 1 shows the incoming solar radiation for a cloudy day and instant of 10 s and mean hourly value at the Freiburg site.

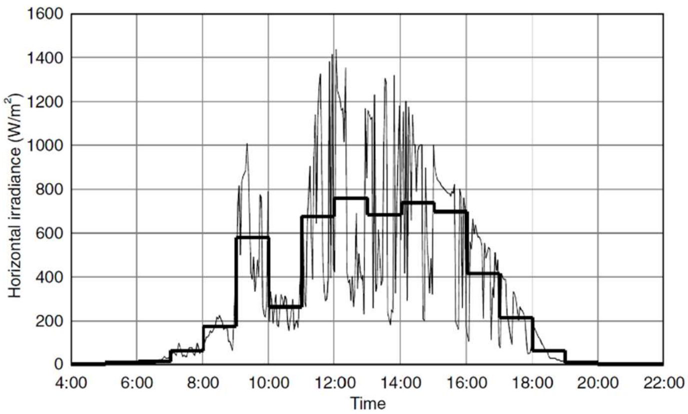

Figure 1. Horizontal irradiance during a typical cloudy day in Freiburg, with instant (10 s) values shown as jagged curve (thin) and mean hourly values shown as stepped curve (thick) [7].

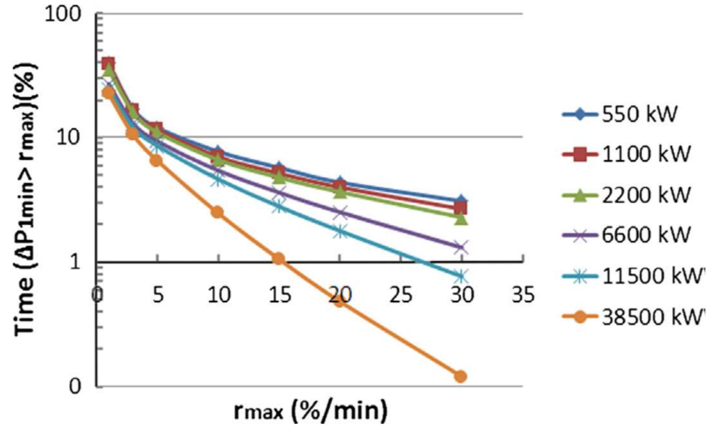

Figure 2. Frequency over one year (July 2010–June 2011) of PV power fluctuations calculated in 1-min time window, DP1min(t), are superior to a given ramp rate (%/min) [4].

As can be noted in fig. 1, the jagged curve (thin) shows measurements of incoming radiation in 10 s intervals which give us an idea of the nature of fluctuations that can be experimented in a particular place (Freiburg in this case), so in mean hourly values represented by stepped curve (thick) we could have fluctuations of minutes and few seconds. More broad and complex analysis about the effect of clouds in the incoming radiation can be found in [8].

III. VARIABILITY OF PV SOURCES

The power generated by photovoltaic (PV) plants have intermittent behavior mainly due to the variability of cloudiness. Since main components of PV plants are PV modules and inverters, the output power generation will quickly follow the incoming radiation pattern, so under these circumstances the characteristics of clouds in term of area covered, speed, optical transmission, and other parameters will heavily affect the energy production [3].

Standard PV plants exhibit power fluctuations that can be either smooth or aggressive based on conditions describe above. For instance, variations up to 90% and 70% per minute have been recorded, at 1MW and 10 MW PV plants [4]. Depending on the level of such fluctuations exhibited by grid-tied utility-scale PV plants, the grid power quality and reliability can be compromised. This issue receives more attention when the PV plants are in an island and geographically dispersed, so the probability that an increment in the penetration of PV affect the grid is high.

A. Power Fluctuation in PV Plants

Based on research studies [4], the power fluctuations in PV plants are inversely proportional to the plant size. Thus, the number of fluctuations at a given ramp rate % per minute in a relatively large PV plant is less than in a smaller one. Fig. 2 shows an experiment carried out in different sizes of PV plants in Amaraleja (South Portugal), results data belong to a full year (July 2010-June 2011).

In fig. 2, *x* axis represents the ramp rate (r_{max}) in %/min and *y* axis represents the number of times, in percentage, a PV plant with power P^* exceed r_{max}. As can be observed, the plant of 550 kW exceeds the ramp r = 1%/min for 40% while the plant of 38.5 MW exceeds the same ramp for 23%. At the same time, for a higher ramp r = 30%/min, these values change to 3% and 0.1%, respectively. From this analysis, if we want to impose a ramp of 10%/min, as it has been required in some regions, an energy storage system is needed.

The power fluctuation in a PV plant can be measured by recording its power output $P(t)$ at certain sampling period, Δt, power fluctuation at time t, $\Delta P_{\Delta t}(t)$ is define as the difference between two consecutive samples of power, normalize to the inverter power P^*:

$$\Delta P_{\Delta t}(t) = \frac{[P(t)-P(t-\Delta t)]}{P^*}100\% \quad (1)$$

B. Case Study of Power Fluctuations in Utility-Scale PV Plant

By looking into the registered events of the *Sistema Eléctrico Nacional Interconectado SENI* (National Electrical Interconnected System) of the Dominican Republic, which is an island, is very common to find events or issues associated with fluctuations on grid-tied utility-scale PV plants. For instance, an event registered on June 09, 2021, at 14:40 describes a frequency drop in the interconnected electric system [9]. Fig. 3 shows step by step this event, the PV plant Montecristi Solar experimented a power generation decreasing from 45.25 MW to 16.31 MW between the time 14:36:26 and 14:38:58. At this moment the PV plant had a total installed capacity of 58 MWp and a nominal output power of 52.8 MW. In fig. 4 by applying (1) to calculate the ramp rate of the output power fluctuation a roughly -27.4% per minute was obtained. The PV plant output power continued decreasing until reach 14.80 MW in the time 14:40:48 and the frequency drop (59.305 Hz) occurred at the time 14:40:36.

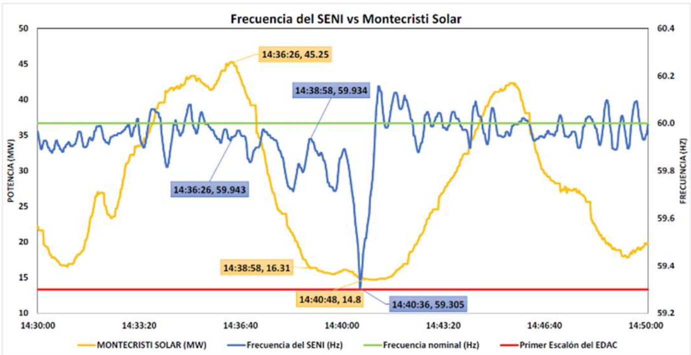

Figure 3. Frequency (Hz) behavior of SENI vs the output power of the PV plant Montecristi Solar [9].

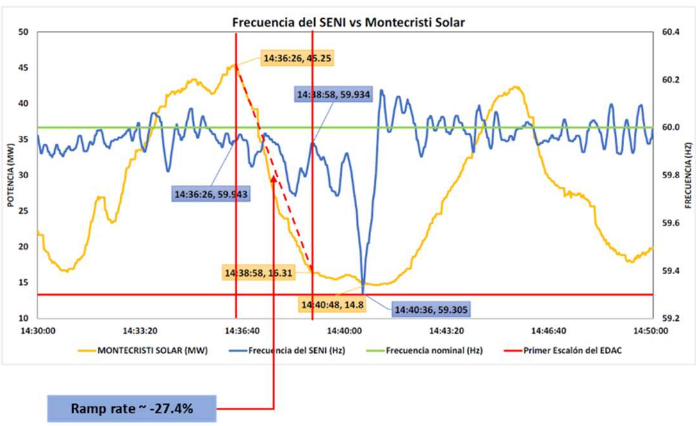

Figure 4. Ramp rate % of the output power fluctuation between red bards is, roughly, -27.4%.

Based on the event report, because the time window where the fluctuation occurred was relative short, the activation of the synchronous generator's spinning reserve was not possible. This is the weakness of traditional dispatchable resources, the limited ability to respond quickly. A reduction in ramp rate is then necessary in grid-tied utility-scale PV plants to no affect the power quality and reliability. In power systems such as island in this case, when there is a high penetration of PV due to large-scale PV plants connected to the grid, there is a risk of high output power ramp rates. As a result, regulations have been introduced to limit the ramp rate, Germany and Puerto Rico is an example of this, they require a maximum ramp rate of 10% per minute of the rate of PV power [10].

IV. SMOOTHING THE POWER FLUCTUATION BY USING BESS

Different ramp rate controllers can be used to smooth the power fluctuation in PV plants, they can vary in term of input variables and control complexity. Fig. 5 shows a simple ramp rate control [4]:

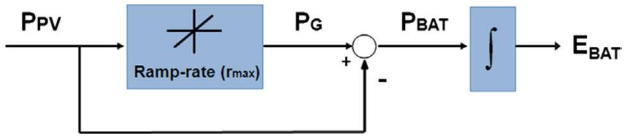

Figure 5. Ramp-rate control model for a given PPV(t) time series. Looking for simplicity, battery and associate electronic converter losses are ignored [4].

PPV(t), *PG(t)* and *PBAT(t)* are, respectively, the power from the inverter, the power to the grid and the power to the battery:

$$P_{BAT}(t) = PG(t) - PPV(t) \tag{2}$$

In the morning, when the PV plant receives the first insulation hours, the inverters will try to inject all its power into the grid $P_G(t) = P_{PV}(t)$. The ramp rate control is activated when the maximum allowable ramp condition is broken:

$$|\Delta P_{G,1min}(t)| > r_{max} \tag{3}$$

The power excess or shortage is either taken from ($P_{BAT}(t) > 0$) or store into ($P_{BAT}(t) < 0$) the battery. The energy stored at the battery, $E_{BAT}(t)$ is control by the integral of $P_{BAT}(t)$ over time. This system can be simulated for any time series of $P_{PV}(t)$. To see the simulation result of this controller and know about other options, please refer to [4], [5].

A. Case Study of Ramp Rate Limitation in Utility-Scale PV Plants

Now we will focus our attention on a utility-scale PV plant located in Africa to add BESS with the purpose of limiting the ramp rate output power to 10% per minute. Currently the PV plant counts with 2 MWp and will be extended to 6 MWp with a total inverter capacity of 5.55 MWac. Exact geolocation and other technical specification will be kept confidential.

The solar resources were obtained from Solargis with 1-minute TMY resolution and time representation 01/01/1999 – 31/12/2021. The utility-scale PV plant was simulated to analyze the worst-case fluctuation and estimate the BESS to limit the ramp rate. After the analysis process the worst-case fluctuation found has a ramp rate of 25.3%, it belongs to the incoming radiation on April-14th of a full year. Fig. 6 shows the output power of the PV plant from 6:00 to 18:00 and the up-right corner graphic shows a better resolution of the time window between 11:44 and 11:45 when the fluctuation occurred. then a BESS of 1.8 MW/MWh was added to the utility-scale PV plant and the maximum ram rate was reduced to 10%, see fig. 7.

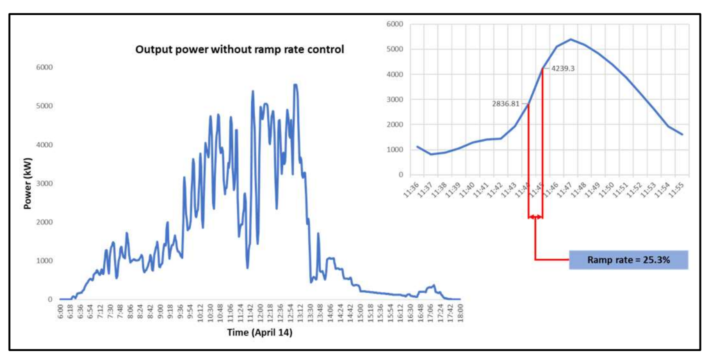

Figure 6. Power output of the utility-scale PV plant in Africa on April 14th. Up-right corner graphic shows a better resolution of the time window (11:44 – 11:45) when the worst-case fluctuation occurred with a ramp rate of 25.3%.

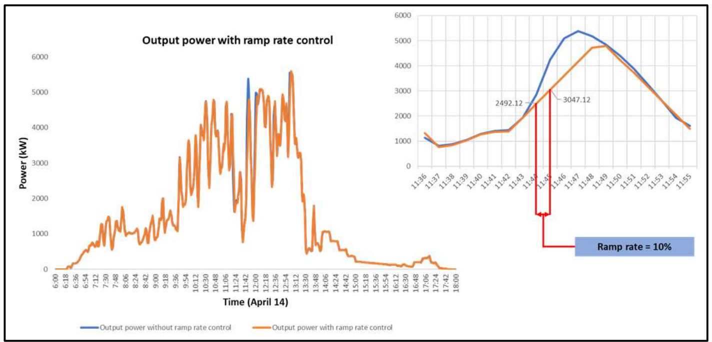

Figure 7. Power output of the utility-scale PV plant in Africa on April 14th with BESS. Blue line represents the output power without ramp rate control and the yellow line represents the output power with ramp rate control, up-right corner graphic shows a better resolution of the time window (11:44 – 11:45) with the output power with and without ramp rate control.

V. Conclusion

In this research we have explained the source of fluctuations in utility-scale PV plants, how those fluctuations affect the grid power quality and reliability, especially when PV plants are in an island, and how to mitigate them by adding BESS to the PV plant. A case study related to an event occurred in the SENI at the Dominican Republic was analyzed to determine the ramp rate of the fluctuation of the utility-scale PV plant Montecristi Solar and how this event affected the power quality this day. Another case study from a utility-scale PV plant in Africa was presented to add BESS with the purpose of limiting the ramp rate at 10%.

Acknowledgment

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cliquet@sollege.com/carlos.liquet@students.uni-freiburg.de