# Inverter-based PV ramp-rate limitation strategies: minimizing energy losses

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***Abstract*—This work analyzes the reduction of power generation in strategies that regulate the PV ramp-rate by using inverter limitation. Although the operating principle implies some energy production losses, not all these losses are necessary. Three different strategies were simulated using experimental 5-second data collected throughout a year at a 38.6 MW PV plant, and their energy losses were obtained for different ramp-rate levels. An improvement in one of these strategies is proposed and evaluated. The main findings suggest that the proposed modification has the potential to drastically reduce annual production losses to insignificant levels. Regardless of the ramp-rate constrain, simulation results evidenced energy losses bellow 1%.**

***Index Terms*—PV smoothing, PV integration, Ramp-rate control, Inverter limitation, Energy losses.**

## I. Introduction

At present, photovoltaic (PV) power is one of the generation technologies with the lowest levelized cost of energy (LCOE) [1]–[3]. As a result, and due to the imperative need to reduce greenhouse emissions, the global installed PV generation capacity has dramatically increased in the past years [4], [5], and this trend is expected to continue in the future. Despite the positive impact of the massive PV installation, it can also put to test the power grid: the intrinsic variability of the solar resource, the current ever increasing upward trend in PV power installation and the reduction in the number of synchronous generators connected to the power system (reducing the grid inertia) have led some transmission system operators (TSO) to impose ramp-rate restrictions to dispatched power from PV and other renewable sources [6]–[11]. The potential issues associated with severe power PV power fluctuations, especially in high penetration scenarios and/or weak grids, include frequency and voltage regulation [12]–[17].

In order to meet these requirements, PV projects must deal with the excess or lack of power during the power fluctuations produced by passing clouds and several strategies have been proposed [18]. Most of them use energy storage systems (ESS), mainly Lithium-ion batteries, to manage the excess or lack of energy: the battery is charged during upward fluctuations and discharged in downward ones, according to the algorithm of each control strategy.

Initially, the analysis of solutions was based on the algorithm (e.g. what type of low-pass filter is suitable), but it quickly became clear that the selected algorithm and its parameters have implications on the required performance of the battery (with its associated cost). Then, the minimum storage and rated power requirements for different solutions were established [19], [20]. In particular, [19] defines the limits of minimum storage and battery power for any specific attenuation level.

It was noticed that, if the use of the battery to smooth upward fluctuations was avoided, then this would reduce its degradation [21]. The above is feasible thanks to the fact that the power point tracking (PPT) of any PV plant can be changed, almost instantaneously, by using its individual power converters. Taking advantage of this fact, the battery would only be needed to smooth downward fluctuations while the PV inverters would regulate the upward ones, for example, by curtailing the generation of each PV converter ($P_{inv}$) whenever its power increases at a faster rate than the defined constraint ($r$) ($\Delta P_{inv} = P_{inv}(k) - P_{inv}(k-1) > r$) [21]. However, such a solution would eliminate the attenuation effect produced by the spatial distribution of PV generators [22], [23] and, as a consequence, there would be considerable annual energy losses, e.g. 9.09% of total production in a facility with peak power of 45 MW and a limitation of 2%/min [21].

Going one step further, and using the same control loop, [24], [25] analyzed the possibility of the coordinated regulation of each PPT, thereby ensuring that the total dispatched power ($P_g$), which is the sum of each inverter production plus the battery power ($P_b$), does not overpass the ramp limitation ($\Delta P_b + \Delta \sum P_{inv} \leq r$). For the same attenuation level (2%/min), and facilities with a rated power of 45 and 10 MW, the annual losses were 2.33 and 3.27%, respectively [24], [25].

This work proposes and evaluates a modification of the strategy in [25] that reduces energy curtailments to insignificant levels, for all attenuation levels ($r$).

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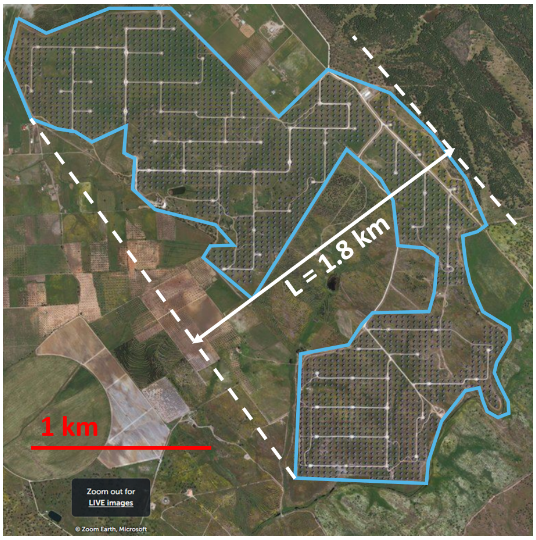
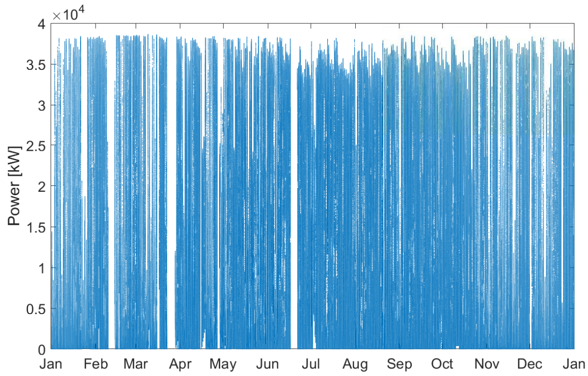



(a)




(b)

Fig. 1: (a) Amareleja PV plant in southern Portugal (38º11'20" N,7º12'8" W), with its perimeter and shortest dimension ($L$). (b) Annual 5-second sampled PV plant series production.

## II. Experimental Data

Data were recorded over one year at the Amareleja PV plant (Fig.1(a)) in southern Portugal (38º11'20"N, 07º12'08"0W). The PV plant comprises 2520 vertical solar trackers, with a tilt angle of 45°, and is spread across an area of 250 ha with a ground cover ratio (GCR) of 0.162. Every 36 solar trackers are grouped together and connected to a 550 kW DC/AC inverter, with a total number of 70 inverters, the plant peak power is 45.6 MW while the inverter rated power ($P_N$) is 38.6 MW.

Synchronized series of every inverter were obtained with a 5-second sampling period. In post-process, the 70 inverter series were grouped in pairs to obtain data with a 1.1 MW nameplate capacity, which is currently more realistic than the original 550 kW, and to reduce computational effort during simulation.

Although some days were missed in the recording process, they are a minimum percentage of the year, as can be seen in the total PV power output (Fig.1(b)).

## III. Methodology

Different inverter limitation based strategies were simulated according to the information available in the corresponding publication [21], [24] [25]. When the published information was insufficient to program the algorithm, the ideal behavior was implemented.

Independently of the strategy, the following set of equations were constraints in each simulation:

$$\begin{aligned} & -r \leq \Delta P_g(k) \leq r \\ & P_{lim}(k) = \Sigma P_{inv}(k) \\ & P_b(k) = P_{lim}(k) - P_g(k) \\ & \Delta E_b(k) = P_b(k-1) \cdot \eta_b^{sign(P_b(k-1))} \\ & \min\{0.05 \cdot P_N, P_{lim}(k)\} \leq P_g(k) \leq P_N \end{aligned} \tag{1}$$

where $P_{lim}$ is the limited PV power (the sum of the individual power outputs of each inverter), $P_g$ is the power delivered to the electricity grid, $E_b$ is the energy stored in the battery, $\eta_b$ is the battery efficiency (assuming values of 90% and 95% in charge and discharge, respectively).

For all the strategies, the battery was assumed to have the minimum storage capacity, which is obtained by following the expression in [19]:

$$C_b = \Delta P_{max} \left( \frac{\Delta P_{max}/P_N}{2 \cdot r} - \tau \right) \tag{2}$$

where $\Delta P_{max}$ is the magnitude of the maximum expected power fluctuation ($0.95 \cdot P_N$ was assumed) and $\tau$ is a parameter that is related to the shortest dimension of the PV plant ($L$, which is indicated in Fig.1(a)):

$$\tau[s] = 42 \cdot L[km] - 0.5 \tag{3}$$

## IV. Ramp-rate limitation using inverters

There are two main benefits to this family of strategies: firstly, any strategy based on inverter limitation is able to function with minimum storage [21], [24]; secondly, compared to other minimum storage strategies [21], the use of the battery is reduced given that is not required in positive power transitions, which prolongs battery life expectancy. However, energy losses associated with inverter limitation could produce a negative financial effect on the project if the price of the wasted energy is either higher than or equivalent to the price of either the purchase or replacement of the battery.

### *A. Non-coordinated Inverters*

In this approach (hereinafter Strategy 1), each inverter limits its own power increase ($\Delta P_{inv}$) up to the maximum allowable value ($r$):

$$\Delta P_{inv}(k) = P_{inv}(k) - P_{inv}(k-1) \leq r \tag{4}$$

Given that the total limited PV power ($P_{lim}$), in the instant $k$, is the sum of the power of each inverter ($N$ in total), the maximum limited PV power increase ($\Delta P_{lim}$)

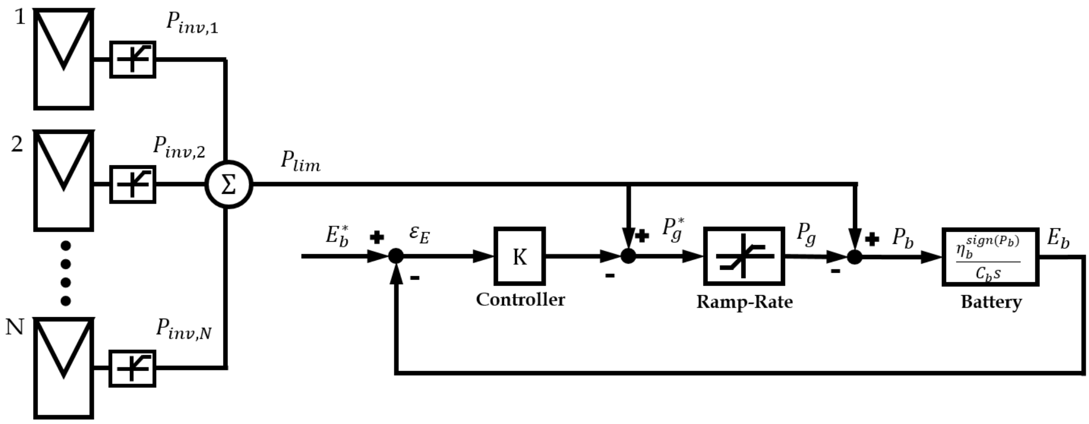



Fig. 2: Control diagram of ramp-rate limitation with inverters.

is guaranteed to be less than or equal to $r$. If the values are expressed in per unit:

$$\begin{aligned} P_{lim}(k) &\leq P_{lim}(k-1) + \sum \Delta P_{inv}(k) \\ &\leq P_{lim}(k-1) + N(r/N) \qquad (5) \\ \Delta P_{lim}(k) &\leq r \end{aligned}$$

The control scheme of the strategy is shown in Fig.2. Its general operation is as follows: the sum of each inverter power output is the limited plant power ($P_{lim}$), the proportional controller provides the desired grid power ($P_g^*$), but it must be limited in order to meet the ramp-rate requirement ($P_g$). The difference between $P_g$ and $P_{lim}$ must be the battery power ($P_b$), its integration (considering battery efficiency $\eta_b$ and total capacity $C_b$) is normalized stored energy ($E_b$), which is compared to energy reference ($E_b^*$) to produce a control action according to the control law ($K$).

A simulated day with $r$=2%/min is shown in Fig.3. The amount of wasted energy is evidenced by comparing the difference between the available PV power ($P_{pv}$, black-dotted line) to the limited power ($P_{lim}$, red line). For this particular day, the energy loss is as high as 32%. In general, for PV plants with identical covered area, the annual losses would essentially depend on the proportion of days with severe power fluctuations.

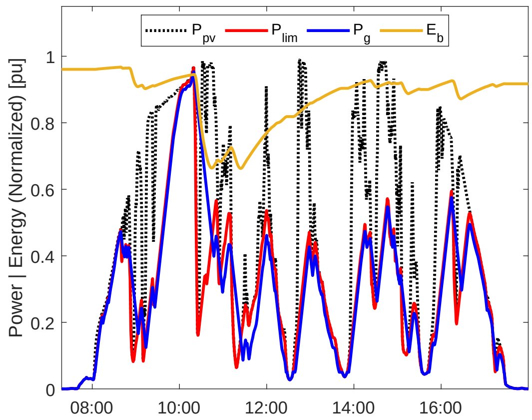



Fig. 3: Strategy 1 behavior, day with severe power fluctuations. Available PV power $P_{pv}$ (black-dotted), limited PV power $P_{lim}$ (red), injected power $P_g$ (blue) and battery energy $E_b$ (yellow).

### *B. Coordinated Inverters*

To modify the PV plant PPT in a desirable way, each inverter needs to be controlled with a central algorithm. The control loop is identical to the one shown in Fig.2, but with communication between inverters and the plant controller.

There are at least two ways to use coordinated inverters. The first one, hereinafter Strategy 2, limits global PPT to ensure that $P_{lim}$ never increases with a higher rate than $r$ [24]. A schematic example can be seen in Fig.4(a).

The second one, hereinafter Strategy 3, initially permits $\Delta P_{lim}$ to be higher than $r$ when a positive fluctuation occurs, and uses the difference between $P_{lim}$ and $P_g$ to charge the battery up to the moment in which the setpoint ($E_b^*$) is reached; from this point onwards, the central algorithm modifies the plant PPT and controls it to ensure that $P_{lim}(k) = P_g(k)$ [25], i.e. operates as Strategy 2. A diagram of the concept is shown in Fig.4(b).

Fig.4 shows that, by comparing the energy losses ($E_{loss}$, green shaded area), Strategy 3 would waste less energy in its attempt to regulate any positive fluctuation than Strategy 2. The simulation results corroborate this outcome for the total year and for the same day simulated in Fig.3. The results are summarized in TABLE I. For one single day with severe power fluctuations (Fig.5), strategies 2 and 3 produce 24.7% and 16.3% less energy, respectively; while the annual losses are 2.5% and 1.9%, in the same order. The improvement compared to Strategy 1 is evident, as the isolated control of the inverters would generate daily losses as high as 32% and annual losses of 6.4%.

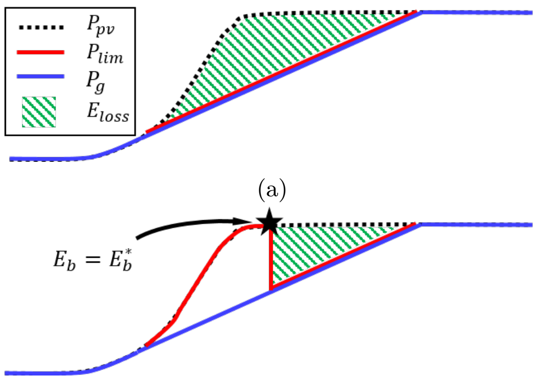



Fig. 4: Schematic concept of strategies with coordinated inverters: Strategy 2 (a) and Strategy 3 (b).

TABLE I: Energy losses as percentage of available energy for two different simulated periods ($r = 2\%/min$)

| Period | Strategy 1 | Strategy 2 | Strategy 3 |
|---|---|---|---|
| Day (with severe power fluctuations) | 32.6 | 24.7 | 16.3 |
| Year | 6.4 | 2.5 | 1.9 |

### C. Causes of energy losses

In strategies with inverter limitation some energy losses are mandatory, however, not all of them are necessary, as is evidenced with the disparity of results in TABLE I. By zooming in on the example day of Strategy 3 (Fig.5(b)), the one with less losses, the causes of unnecessary production curtailment are evident. The detailed view is presented in Fig.6(a), green dashed ellipses (named A and B) were drawn to indicate the main causes of avoidable production losses. In this case, energy wastage is produced when the control loop (Fig.2) produces a charge immediately after a discharge event (downward fluctuation), which is unnecessary given the fact that there is no need to recharge the battery once PV power has reached a low value, precisely because in any forthcoming positive fluctuation the inverters could use part of the potential energy wasted to restore the battery setpoint. Strategy 3 harshly recharges the battery when $P_{lim}$ experiences no sharp power fluctuations (ellipse A), just for waste energy when $P_{lim}$ experienced two consecutive sharp upward fluctuations (ellipse B).

To avoid this kind of aggressive control, which leads to undesirable energy losses, the recommended proportional gain of Strategy 3 ($K = 16[1/h]$) [25] should be reduced, avoiding this and other undesirable effects through battery operation [29]. This approach drastically reduces production losses, as will be seen.

### D. Proposal

Fig.6(a) shows that the control loop has a negative impact on production losses. The only control parameter is the proportional gain (K), which in the original proposal

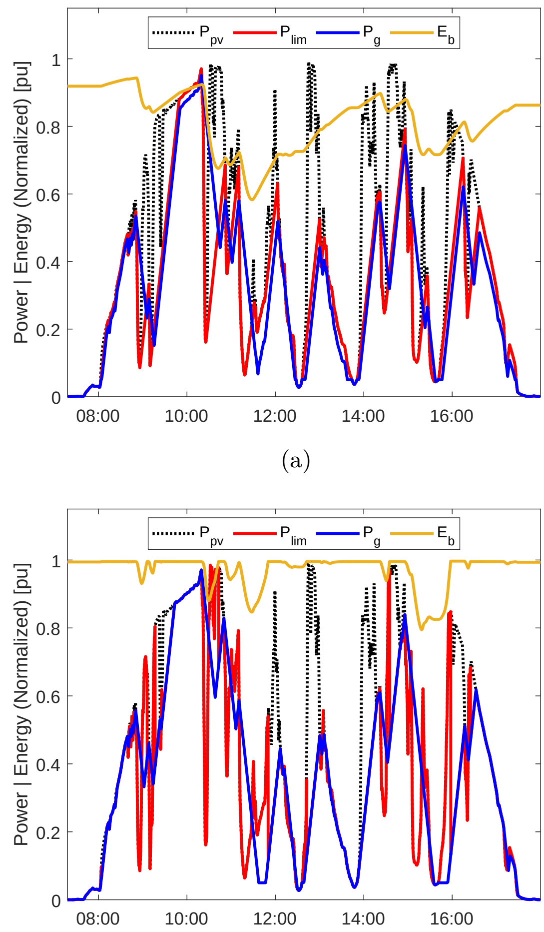


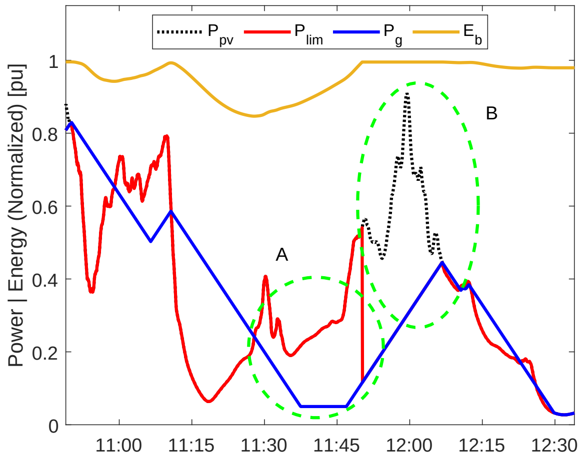

Fig. 5: Same simulated day as in Fig.3. Strategy 2 (a) and Strategy 3 (b). Available PV power $P_{pv}$ (black-dotted), limited PV power $P_{lim}$ (red), injected power $P_g$ (blue) and battery energy $E_b$ (yellow).

[25] has an exaggerated value [29]. Furthermore, there are moments, low production moments, when there is no reason to charge the battery. Principally, the only possible fluctuation is positive, and any charge prior to it would cause an energy wastage of the same magnitude as the said charge (as marked with ellipses A and B in Fig.6(a)).

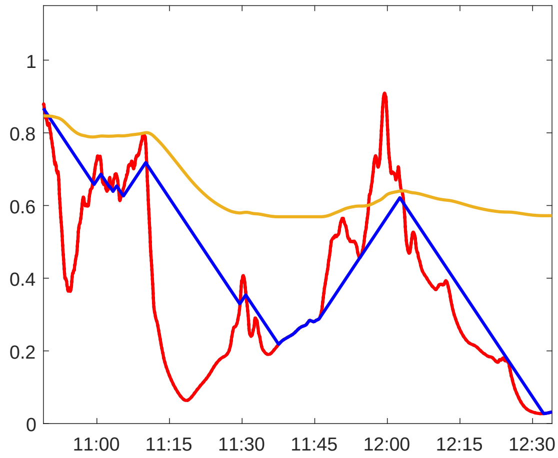
The control action should be neglected in these circumstances, we propose a non-linear proportional control, by making $K$ function of other parameters, e.g. power production ($P_{lim}$):

$$K(P_{lim}) = \max\{0\ ,\ 2 \cdot K_{max} \cdot (P_{lim} - 0.5)\} \qquad (6)$$

Following (6), the proportional gain would take null value if $P_{lim}$ is under the threshold (0.5 pu). From this point, $K$ increases linearly up to $K_{max}$ (0.8 was used). Hereinafter, the proposal is termed Strategy 4.




(a)




(b)

Fig. 6: Causes of production losses of Strategy 3 (a), and proposed improvement (b). Green-dashed ellipses highlight particular moments in which energy losses are unnecessary. Available PV power $P_{pv}$ (black-dotted), limited PV power $P_{lim}$ (red), injected power $P_g$ (blue) and battery energy $E_b$ (yellow).

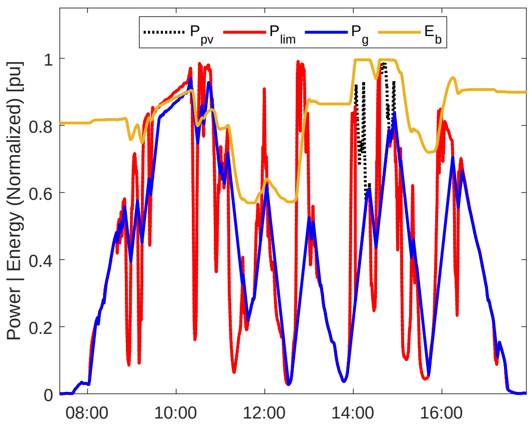



Fig. 7: Simulation result of Strategy 4. Available PV power $P_{pv}$ (black-dotted), limited PV power $P_{lim}$ (red), injected power $P_g$ (blue) and battery energy $E_b$ (yellow).

Strategy 4, on the same day simulated in Fig.3 and Fig.5, exhibits losses of 3.2% (Fig.7), which is a drastic reduction on prior strategies (see TABLE I). Fig.6(b) shows the performance of Strategy 4 in the same time-lapse as Strategy 3. Given the less aggressive control, the energy stored differs from its set point in more instants (the reader can compare Fig.5(b) and Fig.7), but it does not reduce the ability of the strategy to attenuate power fluctuations. The improvement produced by the proposed modification is evident.

## V. Simulation Results

The four strategies were simulated for different ramp-rate limitations with the 5-second sampled data and the annual energy losses for were obtained. Suring simulation, and regardless of the strategy, the set of equations in (1) were met. The results are presented in Fig.8.

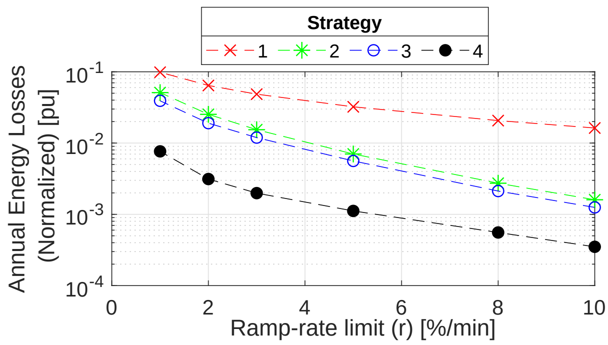



Fig. 8: Annual losses for different ramp-rate restrictions and inverter limitation-based strategies. Strategy 1 (red), Strategy 2 (green), Strategy 3 (blue) and Strategy 4 (black).

It is an evident fact that the harsher the ramp-rate constraint, the higher the energy losses, regardless of the strategy. The energy wasted by Strategy 1 (red dashed line) is more than one order of magnitude above Strategy 4 (black dashed line), the magnitude could be as high as fifty times more losses at $r = 10\%/min$. Strategies 2 and 3 (green and blue dashed lines, respectively) are consistently close to each other, being Strategy 3 the one with less losses in all the cases. For Strategy 1, the implied lack of production would be, in any case, over 1% of the annual generation; while for strategies 2 and 3 the limit of one-percent losses is located around ramp-rate restrictions of 4%/min. The minimum losses (Strategy

4) would be below 1% for all the ramp-rate limitations analyzed, outperforming any of the previous strategies.

## VI. Conclusions

The inverter limitation energy losses of three different strategies to attenuate PV power fluctuations were analyzed and a new strategy was proposed. The strategies were simulated with real data and the results show that the proposal would produce considerably less losses than the previous strategies. The losses of the proposal are below 1% in all cases, and are negligible (under 0.1%) if ramp-rate requirements are less restrictive than 5%/min.

In comparison, the reduction of power production could be more than 1%, and as high as 10% in the case of the severest restriction (1%/min) and the less adequate strategy (uncoordinated limitation of individual inverters). Therefore, the proposed strategy could serve as a reference, in terms of energy losses, to other future PV ramp-rate attenuation methods based on inverter limitation.

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