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Comparison of ramp-rate-based energy storage system control methods for power smoothing of PV systems

Abstract: As the share of highly variable photovoltaic (PV) and wind power production increases, the stability of power grids may be endangered. Issues caused by power fluctuations can be mitigated with ramp rate (RR) limits and energy storage systems (ESS). In this study, 3 different RR-based power smoothing methods for ESSs of PV power plants were compared when the required size and utilization rate of the ESS were considered. This study was based on measured current–voltage curves of a small PV power plant. It was found that even a small modification to the original smoothing method affects the required size and utilization rate of the ESS significantly.

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1 Background and Aims

The share of variable renewable energy sources such as photovoltaic (PV) and wind power is increasing fast in power production. The increasing share of highly fluctuating power production may endanger the stability of power grids. To prevent issues caused by the fluctuating power, multiple countries and regions have set a ramp rate (RR) limit that the grid feed-in powers of power plants must not exceed. For example, Puerto Rico has set an RR limit of 10 %/min [1]. The RR limit is a threshold under which the power fluctuations of the power plants should not cause issues in the power grid. The output power of a power plant can be smoothed to follow the applied RR limit using an energy storage system (ESS). The ESSs can be controlled with different power smoothing methods to achieve the grid feed-in power that follows the applied RR limit. Power smoothing methods that are derived directly from the RR limit are called RR-based power smoothing methods. In [2], an RR-based power smoothing method was introduced and used to study the sizing of the ESSs for PV strings. The power smoothing method used for controlling of the ESS can affect the sizing and

utilization rate of the ESS significantly, as found in [3] and [4], for instance. In [5], the effects of control methods on the sizing of the ESSs was investigated considering the pure RR smoothing, moving average and low-pass filter methods. However, a comparative study considering the effects of different RR-based power smoothing methods on sizing of the ESSs for PV power plants has not been presented.

This paper will study how the use of different RR-based power smoothing methods for the ESSs of PV power plants affects the required size and utilization rate of the ESS. The main objective is to find out which smoothing method would yield the best results when the combination of the size and utilization rate of the ESS is considered. As the PV power fluctuations can be extremely fast, a sampling frequency of 1 Hz or higher would be necessary to detect even the fastest fluctuations, as found in [6]. Thus, this paper will conduct the study with measured PV power that was collected using high enough sampling frequency to give an accurate basis for the study.

2 Materials and Methods

This study is based on measured current–voltage (I–U) curves of a PV string of 23 series-connected PV modules of the PV power research plant of Tampere University [6]. The I–U curves were measured during 25 days in May, June, July and August 2023. The measurement period of each day was from 7:00 to 19:00 (UTC+2). The I–U curves were measured once per second. The global maximum power point powers of the I–U curves were used as the generation power of the PV power plant P_{PV}. The nominal power of each PV module was 190 W, and thus, the nominal power of the PV power plant was 4.37 kW. The length and the width of the PV modules were 1475 mm and 986 mm, respectively. The PV modules were facing nearly southward, and the tilt angle of the PV modules was 45°. The applied RR limit was 10 %/min and all the ESSs of this study were virtual. Considering power of the ESS P_{ESS}, positive P_{ESS} corresponded to charging and negative to discharging of the ESS.

This paper compares three different RR-based power smoothing methods for smoothing of the P_{PV} with an

ESS: the pure RR smoothing method (PRR), an RR-based method used in [2], referred to as L2022, and a modified version of the method used in [2], referred to as L2022M. These abbreviations are used also for the corresponding powers and energies of the methods. The PRR method operates the ESS only when a power fluctuation of the power plant exceeds the RR limit – it does not control the energy level of the ESS at all. The L2022 method smooths the power fluctuations to meet the RR limit and controls the energy level of the ESS so that at every moment the ESS would have enough energy for a sudden shutdown of the power plant. In [2], the minimum amount of energy stored in the ESS at every moment was determined by the grid feed-in power P_{grid}, and it can be expressed as

$$E_{\text{ESS, min}} = \frac{P_{grid}^2}{2RR_{lim}}, \tag{1}$$

where RR_{lim} is the applied RR limit. With the L2022 method, the energy level of the ESS is also kept as low as possible by discharging the ESS whenever possible. The downside of the L2022 is that it will force the ESS to operate continuously even when the P_{PV} would not fluctuate over the RR limit. Another feature that could be considered as a downside is that the grid feed-in power of the L2022 is significantly smoother than the grid feed-in power of the PRR method. In other words, the L2022 method oversmooths the P_{PV}.

The L2022M method smooths the power fluctuations within the RR limit and also controls the ESS so that it would have enough energy for a sudden shutdown of the power plant. The modification is that the energy level of the ESS is not restricted to stay as minimal as possible. By doing this, the ESS should operate considerably less as it is not discharging energy as often as with the L2022 method. As the ESS is not discharging energy excessively during periods when the P_{PV} is decreasing, the ESS often contains more energy than with the L2022 method. As the ESS has more energy, it will meet the minimum energy requirement of Eq. (1) faster once the P_{PV} starts to increase again. This should yield shorter charging times and smaller charging energies with the ESS.

The ESS sizing quantities were the required charging and discharging power capacities and the required energy capacity of the ESS. The ESS utilization rate was presented as the daily share of energy charged to the ESS, which was calculated as the ratio of the daily energy charged into the ESS to the daily produced energy. The energy level of the ESS was zero at the beginning of each day of the simulation period.

3 Results

The measured PV power fluctuated extremely fast occasionally during the measurement period. The
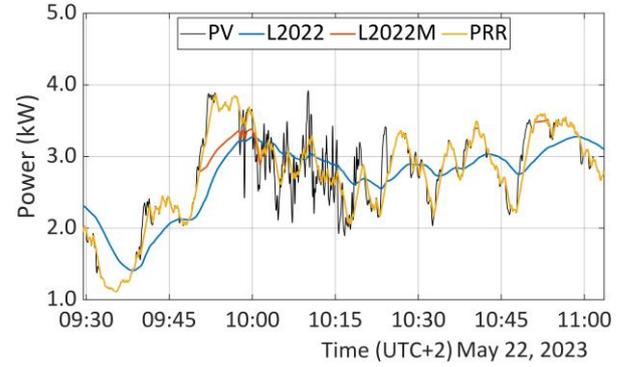

Figure 1. Example of the behavior of the grid feed-in powers of the 3 RR-based power smoothing methods together with the generation power of the PV power plant.
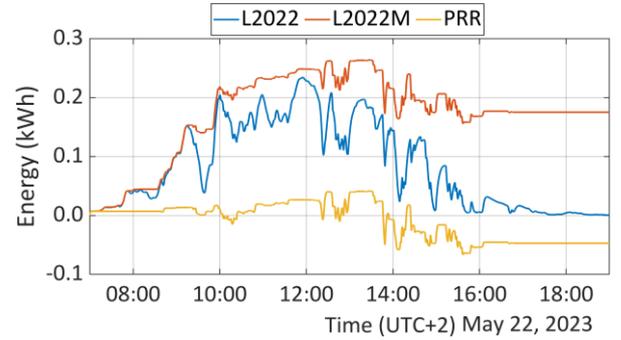

Figure 2. Example of change of the ESS energy level from the initial energy level with the 3 RR-based smoothing methods.

fastest recorded power fluctuations during 1 s were 1314.2 W and 1227.7 W, respectively for the upward and downward power fluctuations. In contrast to the nominal power of the PV power plant, the magnitudes of these power fluctuations were 30.08% and 28.09%. These values are slightly smaller than but still in line with the fastest observed power fluctuations of similar small PV power plants studied in [2] and [7]. Fig. 1 presents an example of the highly fluctuating PV power and the behavior of the grid feed-in powers of the different methods.

Fig. 1 shows that the $P_{grid, PRR}$ followed the P_{PV} closely, as the PRR method only smoothed the fastest fluctuations of the P_{PV}. The $P_{grid, L2022}$ seems to be significantly smoother than the P_{PV} or the $P_{grid, PRR}$. The $P_{grid, L2022M}$ followed the $P_{grid, PRR}$ very closely and was not as smooth as the $P_{grid, L2022}$. The $P_{grid, L2022M}$ was equal to the $P_{grid, PRR}$ most of the time. In general, the $P_{grid, L2022M}$ was differing from the $P_{grid, PRR}$ only when the $P_{grid, L2022M}$ was reaching a new maximum.

Fig. 2 presents an example of change of the ESS energy level from the initial energy level with the 3 RR-based smoothing methods. Fig. 2 shows that $E_{\text{ESS, L2022}}$ was constantly changing as the slope of its graph was never 0, in general. Whereas with the other two methods, the

Table I. Required relative charging powers, discharging powers and energy capacities of the ESS, and daily maximum shares of energy charged to the ESS.

Method	L2022	L2022M	PRR
Charging power (%)	75.9	73.3	73.3
Discharging power (%)	67.7	67.1	69.4
Energy capacity (h)	0.0689	0.119	0.173
Energy charged to the ESS (%)	11.2	8.44	7.67

energy level of the ESS remained constant a major share of time. When the energy level of the ESS remained constant, the ESS was not operating. This means that the ESS was operating a significantly larger share of time when the L2022 method was used to control the ESS.

Table I presents the ESS sizing and utilization results for the different methods. The ESS sizing results are presented as values relative to the nominal power of the PV power plant. Table I shows that the relative charging and discharging powers required for the ESS were quite similar among the different methods. The required relative discharging power values of the methods are quite close to the corresponding value of [2] (74.6%), but there is a notable difference between the required relative charging power capacities of this study and the corresponding value of [2] (90.2%).

All the values of the PRR method are smaller than the corresponding values of [5] in which the ESS sizing was done for a simulated 10 kW PV power plant using the PRR method. The difference in the values is caused by the shorter simulation period and the lower sampling frequency of this study. In [5], a sampling frequency of 10 Hz was used, which makes it possible to detect even the fastest PV power fluctuations, as stated in [6]. Hence, the required size for the ESS was larger, and it was utilized more in [5].

The required relative energy capacities differed significantly among the methods. The smallest value was achieved with the L2022 method, and the highest with the PRR method. The value achieved with the L2022 method is in line with the corresponding value of [2] (0.078 h). The significant difference among the values of the methods is reasonable, as the energy level control of the ESS is significantly different among the methods. In fact, the required relative energy capacity of the ESS with the PRR method resulted from a day during which the energy level of the ESS went considerably negative with respect to the initial level.

The L2022 method yielded the highest daily maximum share of energy charged to the ESS among the methods. This was expected, as the L2022 method forces the ESS to operate continuously. The highest daily maximum
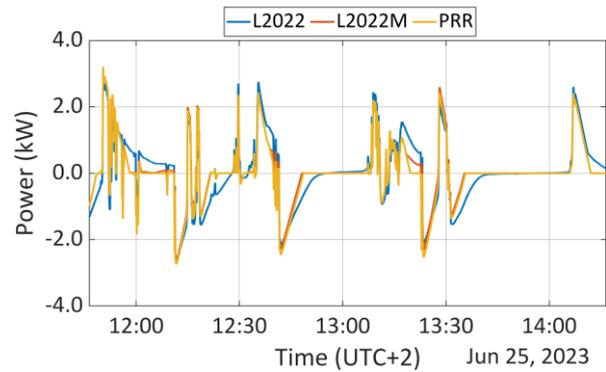

Figure 3. Example of the behavior of the ESS powers of the methods during a day with high power fluctuations.

share of energy charged to the ESS with the L2022 method is significantly smaller than the corresponding value of [2] (17.6%). The PRR method achieved the smallest value for the highest daily maximum share of energy charged to the ESS.

The differences in the ESS utilization among the methods can be seen in Fig. 3 which presents an example of the ESS powers of the methods during the day which yielded the highest daily shares of energy charged to the ESS for the L2022M and the PRR methods. Fig. 3 shows that the $P_{\mathrm{ESS,\,L2022}}$ differed significantly from the other two methods. It can be seen also that the $P_{\mathrm{ESS,\,L2022}}$ was changing continuously even during the periods when the $P_{\mathrm{ESS,\,L2022M}}$ and the $P_{\mathrm{ESS,\,PRR}}$ remained zero. The $P_{\mathrm{ESS,\,L2022M}}$ followed the $P_{\mathrm{ESS,\,PRR}}$ closely most of the time.

The notable differences between the values of this study and [2] regarding the required charging power and the utilization rate of the ESS with the L2022 method, can be explained by the different and longer measurement period that was used in [2] (38 days). The fastest recorded PV power fluctuations during the measurement period of [2] were faster than the ones of this study. Thus, it is reasonable that the measurement period of [2] yielded higher charging power and daily utilization rate for the ESS.

4   Conclusions

It can be concluded that there can be significant differences how different RR-based power smoothing methods affect the sizing and utilization rate of the ESS of a PV power plant. It was found that even a small modification to the original L2022 method lowered utilization rate of the ESS by 25%. But at the same time the required energy capacity for the ESS was increased by 73%. The power requirements for the ESS stayed roughly the same. The energy level control of the ESS seems to have a significant impact on the required energy capacity and the utilization rate of the ESS when RR-based power smoothing methods are considered.

5   Bibliography

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