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Output Power Ramp-Rate Control of a Grid-Connected PV Generator using Energy Storage System

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Abstract: Output power of a photovoltaic (PV) generator depends mainly on incident solar irradiance on the PV modules. Due to moving clouds in the sky, the incident solar irradiance on the PV modules fluctuate frequently. As a result, output power from PV generator also fluctuates. Rapid changes in PV generated power can cause serious problems for relatively small electricity networks with high penetrations of PV generation. Energy storage systems can be used to balance the fluctuations in PV generated output power, thus ensuring a smooth supply of power to the grid. The grid-connected solar PV research power plant equipped with climatic and electric measurement systems in Tampere University of Technology is used to analyse fluctuations in PV generator output power. Different aspects of energy storage utilization have been considered to control the ramp-rate of PV generated output power.

Keywords: Energy storage, irradiance transition, power fluctuation, PV system.

I. INTRODUCTION

Photovoltaic power systems are considered to be a significant part of future electricity generation infrastructure. Widespread implementation of PV power systems is necessary to establish a sustainable and environmentally friendly energy production and consumption system. However, the solar resource is inherently intermittent and the output power from PV generators closely follows the incident solar radiation. Fast fluctuations in generated power occur due to the moving clouds in the sky above the PV modules.

Edges of moving shadows cause fast irradiance transitions, which can be harmful for the operation of PV systems and the electrical grid. Such fast irradiance transitions may cause the grid inverters to be unable to follow the global maximum power point causing losses or mismatch losses. Fast fluctuations of the power fed to the electric grid can also cause power quality and energy balance problems.

Utility grid operators impose various restrictions to regulate grid interfacing of renewable energy sources. As the share of the renewable energy systems is growing, different aspects related to high penetration levels of distributed generation in electric power systems are coming under investigation. Technical requirements such as voltage ride-through capability, reactive power capability, ramp-rate control etc. are being mandated to accommodate large number of PV generators in the power systems [1].

In many countries in the world, restrictions are being imposed to control output power fluctuations from PV generators connected to the utility grid to maintain necessary power quality and reliability in the network. For example, The Puerto Rico Electric Power Authority imposed a 10 % per minute rate of change of output power (based on nameplate capacity) for PV generators [2]. Similarly in Germany, transmission system operators have imposed a positive ramp-rate limit of 10 % per minute of PV generated power [3]. Moreover, curtailment of PV generated power is also required when the power is fed to the grid. For example, a PV system can only inject power up to 70 % of its rated capacity to the grid in Germany [4]. It is, thus worthwhile to study the prospects of using energy storage systems in conjunction with PV inverters to compensate the output power fluctuations. PV power plants are also being required to provide response to primary frequency deviations of real power with the help of energy storage systems [3].

Solar irradiance on the Earth's surface varies on a second, hourly, daily, weekly and annual level and the PV generator output power vary consequently. The least unknown of these and perhaps the most severe to the reliable and economic operation of power systems in the future are fast fluctuations taking place in a second to minute timescale. Partial shading of PV systems has been studied earlier in several papers, e.g. in [5]-[11]. The dynamic operation of PV systems, under partial shading conditions, caused by moving clouds; has been studied by theoretical simulations in [12], [13] and, experimentally in [11], [14]. More closely, the recognition, shape and duration of irradiance transitions cause by clouds have been studied experimentally in [15], [16]. It has been noticed that changes in irradiance and power production due to moving clouds can be very steep and large.

The grid-connected PV research power plant equipped with climatic and electrical measurement systems in Tampere University of Technology (TUT) is used to analyse these fluctuations in generated output power and the energy needed to compensate the fluctuations [17]. Different parameters such as hours of operation, storage capacity, charging and discharging power of the storage system are considered to determine requirements for energy storage to balance the output power fluctuations. The performance of different energy storage concepts with

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different parameter values is analysed with respect to years of climatic and environmental measurements of the PV power research plant.

II. OBSERVATION OF POWER TRANSITIONS CAUSED BY MOVING CLOUDS

High penetration rate of PV generators could pose serious problems to network reliability and stability due to variations in generated output power, which closely follows the incident solar radiation on the PV modules [18]. The natural variability of solar radiation along with the shading effects caused by moving clouds can create a very high rate of change of output power from PV generators. Although the aggregation of geographically dispersed PV power plants can create a smoothing effect in the generated output power, the smoothing effect is intrinsically limited [19]. Thus, fluctuations in PV generated power may result in serious consequences for the electricity grid. Several grid operators around the world have imposed new regulations, which limit the variability of PV generated output power. For example, Puerto Rico Electric Power Authority (PREPA) recently imposed a regulation that the rate of change of PV generator output power cannot exceed the limit of 10 % per minute of the generator's nameplate capacity. This regulation is equally applicable to cases where the rate of change of power is positive or negative or when the curtailment of output power is active [20]. Output power from large-scale grid-connected PV power plants can vary up to 90 % per minute, which is far beyond the limitation imposed by PREPA [21]. Energy storage systems can be used to control the rate of change (ramp rate) of PV generator output power. In such application, the energy storage system charges by subtracting and discharges by adding power to the PV generated power, respectively, to control the ramps in the output power. Because of this operation, the rate of change of output power remains within the set limit and compliance with the regulation is ensured. In this paper, applicability and operation of energy storage systems (ESS) are analysed to control the ramp rates in PV generator output power.

A PV generator rated at 1 kW in Standard Test Condition is assumed in this work and the output power is assumed to be directly proportional to the incident solar irradiance. Further, an ideal energy storage unit with undefined technology, capacity and rating is used to limit the rate of change of the PV generator's output power. The ramp rate limit is defined as 100 W/min (10 %/min of the generator rated capacity) for this PV generator. The PV generator is theoretically connected with the electricity grid by a central PV inverter and the energy storage system operates in parallel with the PV inverter. Daily solar irradiance data received by a PV module of the TUT solar PV power station research plant measured at 10 Hz sampling frequency have been used to simulate the output power of the assumed 1 kW rated PV generator. A moving average of 5 seconds is applied to the solar irradiance data to get rid of the noises in the signal. Ramp rate R of the output power (received irradiance) can be defined as the absolute value of the rate of change of output power as follows

$$R = \left|\frac{dP}{dt}\right| \approx \left|\frac{\Delta P}{\Delta t}\right| = \left|\frac{P(t) - P(t - \Delta t)}{\Delta t}\right|, \tag{1}$$

where P is the output power, t is the time and Δt is the sampling period.

Daily solar irradiance data received by the PV module on May 2012 was used to test detection algorithms of power fluctuations (irradiance transition) and the results corresponding to the ramp rate limit of 10 % of the PV generator capacity per minute (100 W/min for a 1 kW generator) are presented in here. Using a sampling period of 1 s, fluctuations in output power were tested. The need of such a fast sampling is in line with the earlier findings that, changes in irradiance and power production due to moving clouds can be very steep and large [15], [16]. The observed daily time of ramp rates exceeding the ramp rate limit of 100 W/min are shown in Fig. 1.

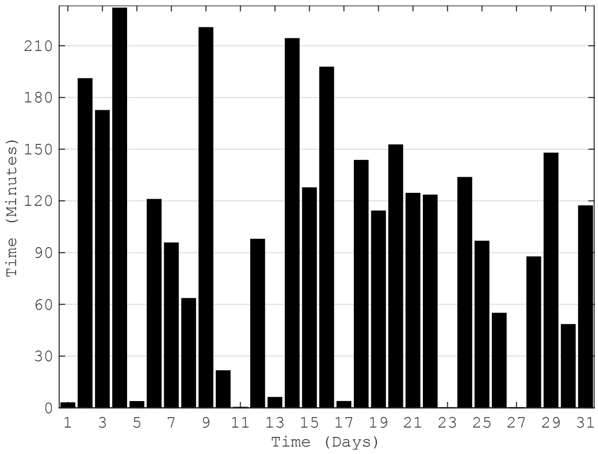

Fig. 1. Observed daily time of ramp rates higher than the ramp rate limit of 100 W/min on May 2012 by using a sampling period of 1 s.

It is interesting to note from Fig. 1 that daily time of ramps with decreasing or increasing output power higher than 10 %/min of the power plant nominal power varies from few minutes up to 4 hour. The average daily time of these high ramp rates was actually over 100 minutes on May 2012. These high times of irradiance rises and drops are actually a big surprise even for a local citizen. To become convinced of the correctness of the analyses, one needs to look at the data more closely. The original daily irradiance with the highest time of power ramps in Fig. 1 on 3rd of May 2012 is presented in Fig. 2 showing high volatility of solar irradiance. Figs. 1 and 2 demonstrate that power fluctuations of PV power production is a major phenomenon and the use of energy storages must be considered to compensate fluctuations to ensure power balance and quality.

In addition, the significance of the variability of solar irradiance and the resulting output power fluctuations can be demonstrated by analysing the high ramp rate data for a whole year. In Fig. 3, the average daily high-ramp-rates are shown for each month in the year 2012.

It can be observed from Fig. 3 that in summer months, on average, the daily ramp rate fluctuations occurred for more

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than an hour in the year 2012. This finding shows that the variability and fluctuations in output power from grid-connected PV generators could be a huge concern for grid operators.

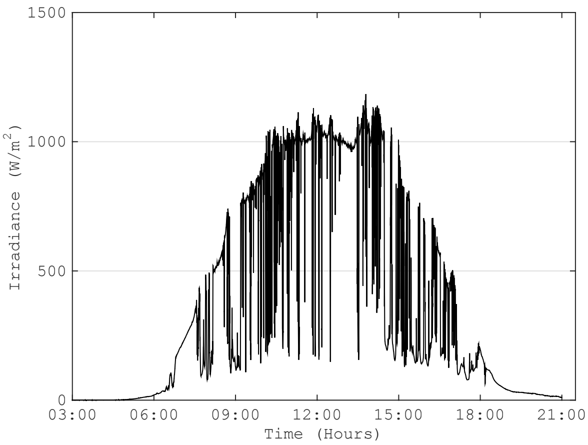

Fig. 2. Solar irradiance received by a PV module on 3rd of May 2012.

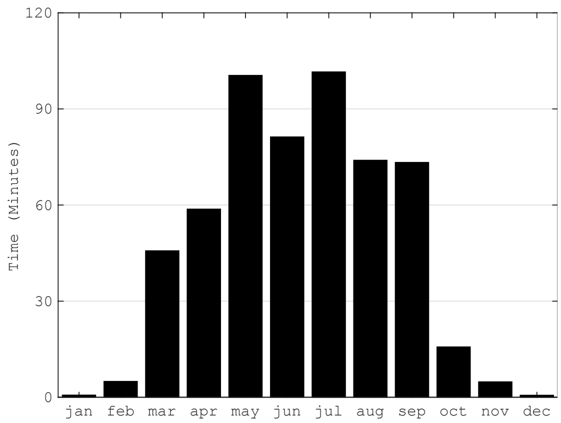

Fig. 3. Average daily times of high ramp rates shown for each month in the year 2012.

III. Analysis of ESS Operation

An ideal energy storage system (ESS), without any defined technology, capacity and rating is theoretically used to balance the output power from the PV generator. As established earlier, the specified ramp rate limit of 100 W/min for a 1 kW generator (10 %/min of rated power) is applied. When the output power of the PV generator decreases faster than the ramp rate, ESS feeds power to the grid so that power received by the grid decreases only with the ramp rate limit. When the output power of the PV generator increases faster than the ramp rate, ESS stores power so that power received by the grid increases only with the ramp rate limit, accordingly. When the rate of change of output power from the PV generator doesn't exceed the ramp rate limit, the ESS does not interfere with the PV generator output power. At that point, it is considered as normal condition of operation and the output power from the PV inverter goes directly to the electricity grid.

The control system in the ESS actively checks the rate of change of inverter output power in every second. When the rate of change of PV generator output power exceeds the specified ramp rate limit, the ESS is activated. If the output power increases at a rate, which exceeds the ramp rate limit, it is referred to as positive ramp deviation. Similarly, when the power decreases at a rate higher than the specified ramp rate limit, it is referred to as negative ramp deviation. During positive ramp deviation, the ESS stores as much power as needed (by subtracting from the PV generated power) to maintain a steady ramp of 100 W/min. During negative ramp deviation, the ESS discharges and adds power to the PV generator output to maintain a steady ramp of 100 W/min. The operation of the storage system can be observed in Fig. 4 for 10 minutes in the morning of 3rd of May 2012.

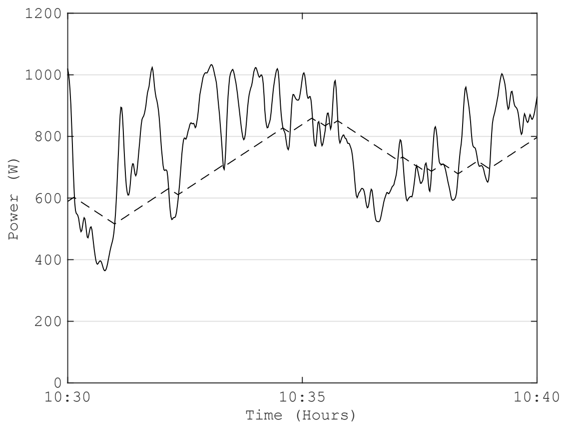

Fig. 4. The operation of the energy storage system for 10 minutes in the morning on 3rd of May 2012 is shown. PV generator original output power is shown with the solid line and the output power compensated by the energy storage system with the dashed line.

A basic application scenario of the energy storage system is considered in this paper, where the ESS controls the rate of change of the PV generator output power when the PV inverter is rated at 100 % of the PV generator capacity. At first, the ESS operates periodically. Required capacity of the ESS when operating periodically (daily) can be found by analysing the performance of the ESS. Secondly, The ESS operates continuously for one year. At the end of the paper, the operation of the ESS when power curtailment is active is discussed briefly. When power curtailment is active, the PV inverter operates at 70 % of the PV generator capacity. The objective is to analyse the operations of the energy storage system in order to size suitable energy storage systems for practical operations. By analysing the periodic and continuous operations of the ESS, information such as the required power rating, capacity and cycle for practical applications can be obtained.

A. Periodic Operation of the ESS

Periodic operation of the ESS was simulated against the measured solar irradiance received by a PV module of the TUT research plant in 2012. In periodic operation, the ESS charges and discharges as necessary to balance the ramp rate of the PV generator output power. At the end of each day, the ESS is reset and the ESS starts the next day with zero stored energy. In Fig. 5, the daily maximum energy values stored by the ESS for each day of the year 2012 are shown in descending order of the energy values.

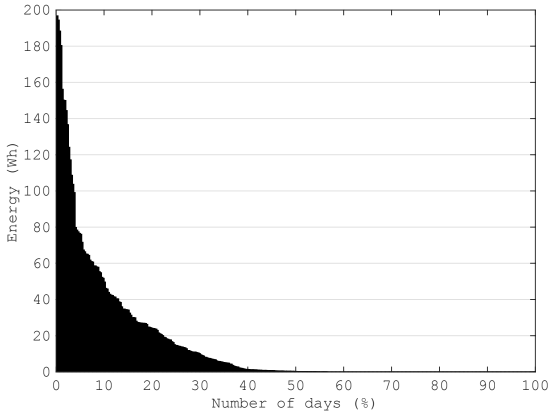

Fig. 5. Daily maximum energy stored by the ESS, in each day of 2012.

For 80 % of the days, the maximum energy capacity reached by the ESS was lower than 20 Wh, as can be seen in Fig. 5. Daily maximum energy discharged by ESS in each day of 2012 is shown in Fig. 6. It can be observed from Fig. 6 that the ESS did not discharge any energy during 40 % of the days in the year 2012. For 90 % of the days in the year 2012, maximum energy discharged was less than 100 Wh. Maximum energy discharged by the ESS, was 568 Wh in year 2012.

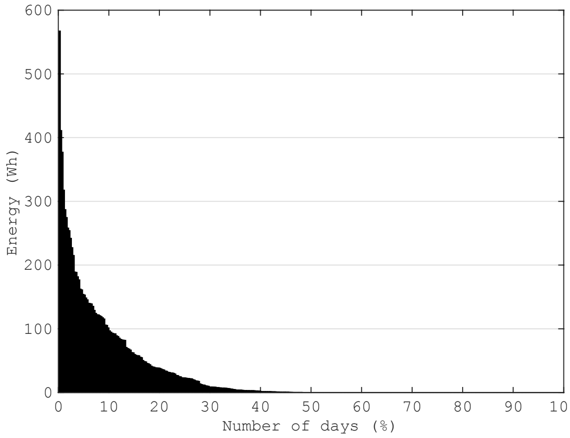

Fig. 6. Daily maximum energy discharged by the ESS, in each day of 2012.

A daily energy storage capacity of around 200 Wh seems to be enough for storing energy but for discharging energy to the grid, almost 600 Wh is needed. This implies that energy storage of the order of 800 Wh might be needed to compensate all power fluctuations, if ESS is charged to have 600 Wh of energy every morning to be able to compensate all power fluctuation during the day. It can be seen from Figs. 5 and 6 that there are practically no radiation and power fluctuations during half of the days in the year 2012. Most of these days are winter time days from October to February, when Sun is not rising very high above the horizon in Finland. Days are also often fully cloudy during autumn time in contradiction to typical half cloudy days during summer time. It is also notable, that power fluctuation during 96 % of days in 2012 could have been compensated with energy storage of 300 Wh.

Energy remaining in ESS at the end of the operation in each day is shown in Fig. 7. Negative value of energy at the end of a day means that energy has been delivered more that stored during the day. In the case of positive values it is vice versa.

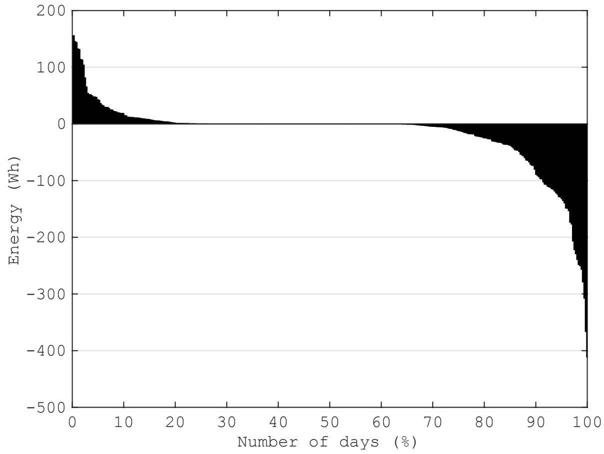

Fig. 7. Energy remaining in ESS at the end of the operation in each day of the year 2012, shown in descending order.

B. *Continuous Operation of the ESS*

A simulation of the operation of the energy storage system has been done, where the energy storage remains active without any recharging for a full year. The energy storage unit charges and discharges itself as described earlier to keep the ramp rate of PV generator output power under the limit of 1.6667 W/s. Total charging and discharging times in 2012 were 267 and 279 hours, respectively. Distribution of charging and discharging power of ESS in 2012 is shown in Fig. 8.

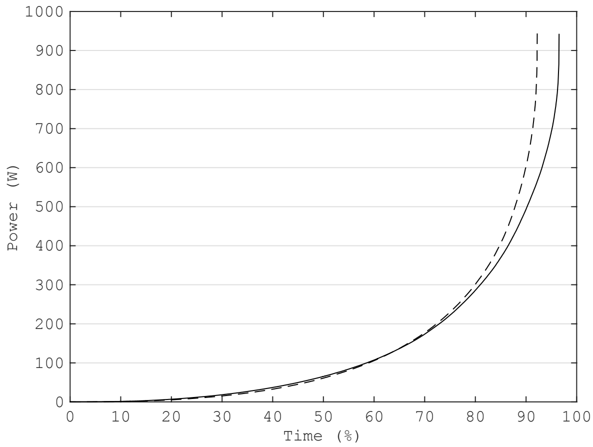

Fig. 8. Charging and discharging power of ESS are shown with dashed line and solid line, respectively.

The maximum charging power of ESS was 960 W and the maximum discharging power was 942 W. In 80 % of cases with positive ramp charging power is below 200 W and in over 90 % of cases below 400 W. In Fig. 9, the state of energy in the ESS is plotted when the ESS operates continuously for the year 2012.

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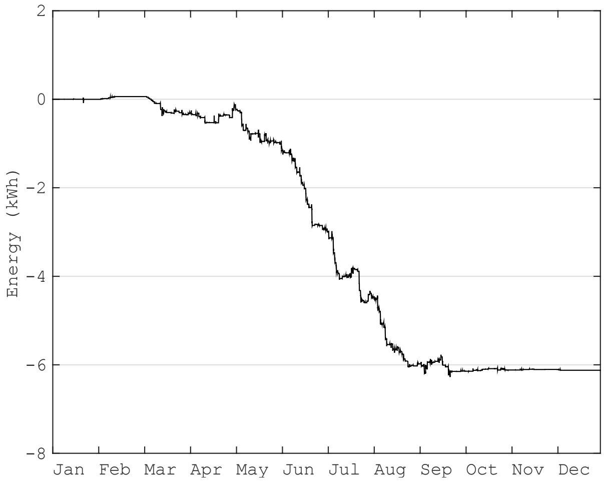

Fig. 9. The ESS operates continuously throughout the year 2012.

From Fig. 6.9, it can be seen that the ESS loses very little energy during the winter months of January, February, October, November and December in the year 2012. The discharge of the battery is significant in summer months of May, June, July and August. The energy of the battery was near 0 kWh at the start of May and the energy of the battery was around -6 kWh at the end of August. At the end of December 2012, the state of energy in the battery was around -6.12 kWh. As a result, the ESS can be operated for a whole year and then, it only needs a little more than 6 hours of the plant's capacity to be recharged.

C. Curtailment of Output Power is Active

In this section, it is assumed that the PV inverter is rated at 70 % of the PV generator capacity. This method is undertaken to reflect the imposed regulations in many places in the world. In the case of grid-connected PV generators, power curtailments are applied due to the intermittent nature of the PV systems. Power curtailments are achieved by using PV inverters having less capacity compared to their respective PV generators. For example, in this case, the PV inverter is rated at 70 % of the PV generator capacity.

Thus, the inverter does not inject more than 700 W of PV generated power in to the electricity grid. As a result, the required capacity of the ESS in this section should be different from the capacity required when the inverter was operating at 100 % of the generator's capacity. As the inverter flattens the maximum output power at 700 W, the ESS should also operate for less time. It was found that the ESS charged for 216 hours and discharged for 228 hours, which are less than the times observed earlier, respectively.

Maximum power during charging was around 578 W. Maximum discharge power of the ESS was 626 W. During periodic operations, the maximum energy charged by the ESS was around 87 Wh and the maximum energy discharged by the ESS was around 567 Wh. The continuous operation of the ESS is shown in Fig. 10. At the end of the year 2012, the state of energy in the ESS was -5.24 kWh, which roughly translates to 5 hours of plant capacity.

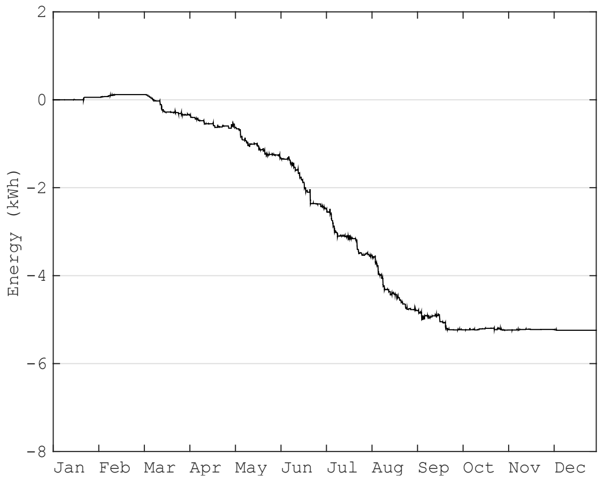

Fig. 10. The ESS operates continuously throughout the year 2012, when the power curtailment is active.

IV. CONCLUSION

The results shown in this paper demonstrate the potential of the extensive climatic and electrical database measured by the TUT solar PV research power plant to analyse output power fluctuations and their compensation via energy storage systems. The results also demonstrate that irradiance and PV power plant output power fluctuations are fast with ramps lasting from seconds to minutes. Therefore, PV power plant measurements with a sampling frequency of at least 1 Hz are needed to study these phenomena.

The analyses revealed that of the order of 800 Wh of energy storage capacity is needed to ensure that all daily power fluctuations of a 1 kW PV generator are compensated when a ramp rate limit of 100 W/min is required. This result serves as an upper limit for the required storage capacity, because charging and discharging of energy storage was done only during power ramps exceeding the ramp rate limit. A lower limit for the storage capacity is obtained if only each single ramp (up or down) needs to be compensated. Then 100 Wh of storage capacity is enough to compensate even the fastest and highest ramps. In this case energy storage should be charged or discharged between power ramps to maintain the capacity in use. However, for designing this kind of energy storage system in practice requires further research.

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REFERENCES

[1] A. Woyte, V.V. Thong, R. Belmans, N. Nijs, IEEE Transactions on Energy Conversion, 21 (2006) 202.
[2] Puerto Rico Electric Power Authority, "www.fpsadvisorygroup.com" 2012. Available: http://www.fpsadvisorygroup.com/rso_request_for_quals/PREPA_Appendix_E_PV_Minimum_Technical_Requirements.pdf. [Accessed 09 February 2014].

[3] V. Gevorgian, S. Booth, Review of PREPA Technical Requirements for Interconnecting Wind and Solar Generation, National Renewable Energy Laboratory (NREL), (2013).

[4] O. Franz, B. Barth, "www.pvgrid.eu" 22 October 2013. Available: http://www.pvgrid.eu/fileadmin/6. Germany_131022_PVGRID_RWE_BSW.pdf. [Accessed 05 February 2014].

[5] K. Ishaque, Z. Salam, Syafaruddin, Solar Energy, 85 (2011) 2217.A. Bidram, A. Davoudi, R.S. Balog, IEEE Journal of Photovoltaics, 2 (2012) 532.

[6] A. Bidram, A. Davoudi, R.S. Balog, IEEE Journal of Photovoltaics, 2 (2012) 532.

[7] M.Z.S. El-Dein, M. Kazerani, M.M.A. Salama, IEEE Transactions on Sustainable Energy, 4 (2013) 99.

[8] Y.J. Wang, P.C. Hsu, Energy, 36 (2011) 3069.

[9] H. Patel, V. Agarwal, IEEE Transactions on Energy Conversion, 24 (2008) 302.

[10] A. Mäki, S. Valkealahti, IEEE Transactions on Energy Conversion, 27 (2012) 173.

[11] A. Mäki, S. Valkealahti, Renewable Energy, 71 (2014) 89.

[12] K. Lappalainen, A. Mäki, S. Valkealahti, 28th European Photovoltaic Solar Energy Conference and Exhibition, (2013) 4081.

[13] C.R. Sánchez Reinoso, D.H. Milone, R.H. Buitgaro, Applied Energy, 103 (2013) 278.

[14] E.C. Kern, E.M. Gulachenski, G.A. Kern, IEEE Transactions on Energy Conversion, 4 (1989) 184.

[15] T. Tomson, Theoretical and Applied Climatology, 112 (2013) 403.

[16] T. Tomson, Solar Energy 84 (2010) 318.

[17] D. Torres Lobera, A. Mäki, J. Huusari, K. Lappalainen, T. Suntio, S. Valkealahti, International Journal of Photoenergy, 2013 (2013) Article ID 837310.

[18] C.A. Hill, M.C. Such, D. Chen, J. Gonzalez, W.M. Grady, IEEE Transactions on Smart Grid, 3 (2012) 850.

[19] J. Marcos, L. Marroyo, E. Lorenzo, M. García, Progress in Photovoltaics: Research and Applications 20 (2012) 226.

[20] J. Marcos, O. Storkël, L. Marroyo, M. Garcia, E. Lorenzo, Solar Energy, 99 (2014) 28.

[21] J. Marcos, L. Marroyo, E. Lorenzo, D. Alvira, E. Izco, Progress in Photovoltaics: Research and Applications, 19 (2011) 218.

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