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Monitoring of Storage Systems in Subgrids with Photovoltaic Power Generation – Addendum to the Guidelines for Assessment of Photovoltaic Plants, Document A

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Contents

Foreword

The 2016 Clean Energy for All Europeans Package is addressing renewable energy, energy efficiency, market design and governance together with security of electricity supply. On the path towards climate-neutrality, both techno-economics and energy-security of the power grids under high-shares of renewable energies are of central importance. For the distribution grids, large-scale integration of decentralized photovoltaic power generation with rapid fluctuations and power peaks above consumption peaks, becomes quite demanding. Complementary to infrastructure reinforcements, the allocation of distributed storage allows to balance fluctuations and to equip the power grid with static inertia. It is thus removing barriers for accommodating photovoltaic power generation, increasing local direct consumption and sector coupling, also contributing to risk preparedness and supply security.

Abstract

With decreasing cost and its rising share in the power mix, photovoltaic generation is increasingly supported by grid-coupled storage systems. For their inclusion in the performance monitoring framework established, the monitoring guideline specifies the allocation of measurements and the decomposition of data records into directed power flows.

Normalized to system-size and in different timeframes, the directed power flows provide the basis for monitoring of storage performance in the system context, provision of flexibility and contracting of ancillary services. They lead to evaluation of system sizing & operation quality in comparable form, subject to further specification of analysis and presentation of monitoring data.

Spatial aggregation in recursive structuring allows to provide consistent larger area views, employing the same performance evaluation and analysis tools. The data monitored delivers information about reserve against real-time bottlenecks, safeguarding of market access, long-term adequacy and risk preparedness, as well as statistics indicators.

1 Introduction

For the Assessment of Buffered Grid Integration of Photovoltaic (PV) Power Generation, likewise applicable to grid integration of other generation from renewable energies (RE) and to sector coupling, this document covers Monitoring of Storage Systems in Subgrids. It follows the structure of and is complementing the JRC Guidelines for Assessment of Photovoltaic Plants - Document A Photovoltaic System Monitoring [1], developed for the direct-current (DC) coupled systems of the European Photovoltaic Demonstration Programmes. The related Document B Analysis and Presentation of Monitoring Data [2] was applied when starting with the first MW of photovoltaic power installed between 1982 and 1984 in 15 PV plants. Through performance monitoring of more than 150 projects, comprehensive experience could be gained in the complete range of applications [3], and results of the projects were guaranteed, as JRC support for the implementation of EU policies.

In the meantime, with PV generation considerably increasing, alternative-current (AC) coupled inverters have become common, with the Guideline accordingly updated [4]. In support of high shares of PV generation in the grids, accordingly AC-coupled Storage Systems are becoming relevant. They contribute to

- perform local balancing
- keep subgrid interconnections open for market access
- avoid/defer infrastructure extensions
- provide ancillary services
- foster internal economic benefits

in their respective subgrids. Analytical monitoring is recording detailed information about their operation, as relevant for further assessment. It is based on separating the metering of stored and restored energy within the subgrid assigned, from metering of stored and restored energy from and to the utility grid. Power-flow restrictions at utility grid interconnection, resp. their reserves, are exhibited, relevant for supply security and open market access.

This guideline provides the information, which is necessary for implementation of the monitoring, as required for metering and performance evaluation of storage systems within their power grid environment. Beyond providing feedback to system operators, assessment of performance is of more comprehensive interest, considering system-relevant storage operation under different aspects and in different timeframes from real-time bottlenecks and market accessibility, further to markets interaction, long-term adequacy and risk preparedness.

2 Requirements for Analytical Monitoring

2.1 Allocation of Measurement Devices

For operation of storage in different grid situations, critical power-flows - typically through transformers, lines or cables - are taken into account in defining subgrid areas.

Subsequently, the denominations

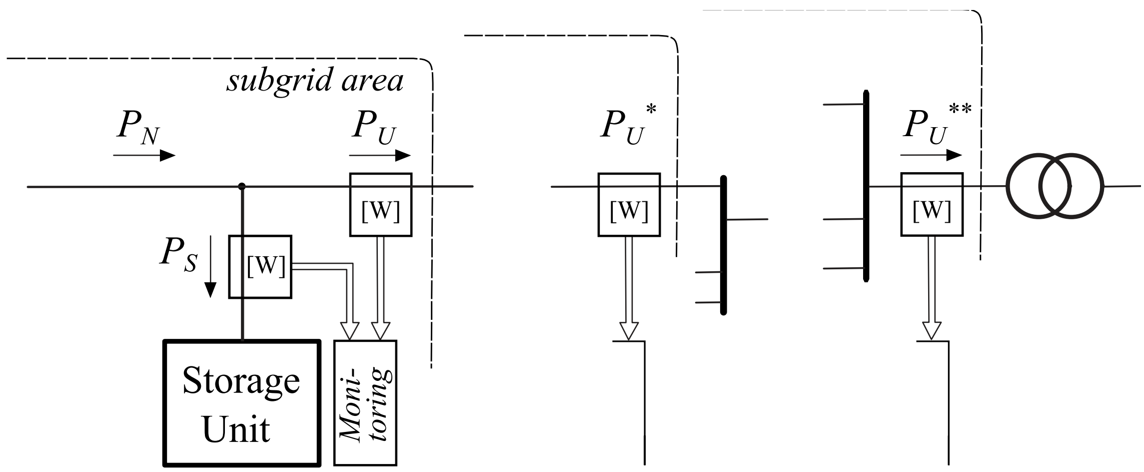
Subgrid : Set of loads, generation and storage units within a subgrid area as system border, separable at defined power grid interconnection points; as active subgrid controllable in grid-parallel or off-grid mode

Storage Connection Point (SCP) with active power P_S **:** bidirectional, sign-separated active power measurement of feed-in and fed-out power $(P_S)^+ = P_{TS}$ and $(P_S)^- = P_{FS}$.

Utility Interconnection Point (UIP) with active power P_U **:** bidirectional, sign-separated active power measurement of feed-in and fed-out power $(P_U)^+ = P_{TU}$ and $(P_U)^- = P_{FU}$.

are being used. In case of several Storage Connection Points and/or several Utility Interconnection Points, measurement equivalents can be provided as sum of parallel measurements. Then, in addition to overall performance, often individual shares are of interest. The Data Recording Format shall thus allow for their separate recording.

Figure 1. Allocation of Measurements to Storage Unit



Source: JRC elaborations 2020

According to Figure 1, for subgrid area system borders at some typical grid locations, there are measurements of active power P_U in $[VA] = [W]$ unit [1] required, usually for three phases, summed up and with averaging in decomposed form, to properly represent electrical energy.

This corresponds to separate feed-in and fed-out metering devices for generation and load consumption, and should comply with their precision resp. allow for recalibration. Their short term metering data $\overline{E_{\tau+}}$ and $\overline{E_{\tau-}}$ in intervals τ_{meter} can be used to provide the comparable average power in form of

$$P_G = \overline{E_{\tau+}}/\tau_{meter} \text{ and } P_L = \overline{E_{\tau-}}/\tau_{meter} \ .$$

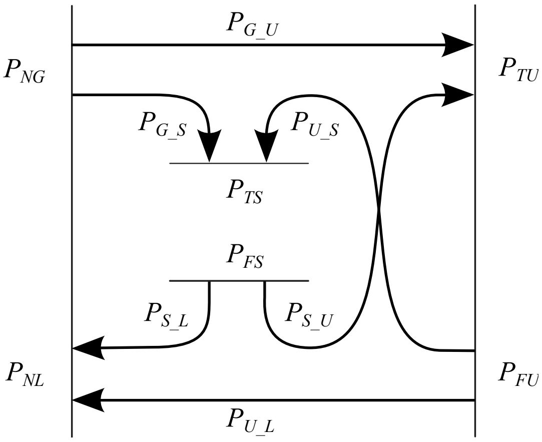
1 reactive power measurements Q can optionally be included

As $P_N = P_U + P_S$ is uniquely defined, the measurements are equivalent to combined metering before and behind storage.

2.2 Decomposition of Power-Flows

The relation between directed power-flows is resulting according to Figure 2. In the power balance of a subgrid area, a surplus of net-generation over utility feed-in flows is balanced by storage, as well as the deficit of net-load against utility fed-out flows.

Figure 2. System- and Utility-Side Power-Flows



Source: JRC elaborations 2020

This allows for determination of the remaining power-flows.

Subgrid Surplus/Deficit Shares			
Net-Generation to Storage	P_{G_S}	$(P_{NG} - P_{TU})^+$	as surplus of $P_{NG} > P_{TU}$
Storage to Net-Load	P_{S_L}	$(P_{FU} - P_{NL})^-$	as deficit of $P_{FU} < P_{NL}$
Allocation of Utility Grid Shares			
Generator to Utility	P_{G_U}	$P_{NG} - P_{G\_S}$	
Storage to Utility	P_{S_U}	$P_{FS} - P_{S\_L}$	
Utility to Storage	P_{U_S}	$P_{TS} - P_{G\_S}$	
Utility to Load	P_{U_L}	$P_{NL} - P_{S\_L}$	

Arranged in matrix form, Annex A shows the mapping and the inverse mapping, suitable as check for data consistency.

For further performance evaluation, typically the amount of load coverage by generation from renewable energies, either total averaged power from generation P_G itself or from load consumption P_L, are needed from metering over longer time-spans. Aggregated for the subgrid, they are related by $P_G - P_L = P_{NG} - P_{NL}$ with net-generation and net-load power-flows before storage. Thus, direct power-flow from generation to load P_{G_L} is determined

Direct Generation to Load Share		
from Total Generation Aggregated	P_{G_L}	$P_G - P_{NG}$
or from Total Load Aggregated	P_{G_L}	$P_L - P_{NL}$

completing the set of power-flows.

3 Data Processing and Evaluation

3.1 Recording Format

Data should be written in directly readable form. Details of the recording format are given in ANNEX B.

The recording format follows the principle to use a common dataset for different evaluations. Whereas primary measurement with grid-period 20ms-sampling are assumed, pre-processing allows for averaging over larger time-periods, depending on the performance analysis in view. E.g. minute time-periods would allow for reasonable resampling to 10-15min intervals, matching intraday market intervals.

Subgrid/storage/utility connection records appear regularly, at each sample period for the complete timespan covered. Storage-technology specific, total generation/load and event records may be sampled less frequently.

Completed recordings should be forwarded by the Monitoring/System Operator, covering periods of not less than one month and not more than 3 months, together with further information helpful for interpretation and evaluation of data.

3.2 Processing and Evaluation

The data received from stations with analytical monitoring are included in a database with preparation of reports summarising main results for the period[2]. For unified assessment and comparison of stations in a wider range of nominal powers, they refer to normalized power averages. Energies from the directed powerflows, normalized to different timeframes and nominal powers P^0 of utility-connection or PV-generation are used, denominated as yields Y. The yield summaries for

Generation	Y_G	**Balancing**	Y_L	Y_G
total load	Y_L	direct supply	Y_{G_L}	Y_{G_L}
buffer-recharge	$Y_{TS} - Y_{FS}$	storage buffered	Y_{S_L}	Y_{G_S}
net utility feed	$Y_{TU} - Y_{FU}$	utility balanced	Y_{U_L}	Y_{G_U}

represent the energy-balances. Typically, monthly/annual yields $Y_{month/year}$ for the directed power-flows recorded, serve as basis for performance indicators, allowing for brief assessment of overall quality of sizing & operation in comparable form. Further, characterizing surplus-energy percentage vs. load demand as ratio $r_{SE} = (Y_{TU} - Y_{FU})/Y_L$, and self-balancing percentage vs. load demand as ratio $r_{SB} = (Y_{G\_L} + Y_{S\_L})/Y_L$ give indications of the contribution to climate-neutral energy supply.

3.3 Further Analysis

On basis of the data recorded, further detailed analysis can include temporal correlations between subgrid and utility-side power-flow shares in the complete range of different timespans. Here, e.g. the buffer-depth range E_B in operation is of interest, relative to the nominal energy storage-depth available. Correlation with generation and consumption profiles are of relevance for allocation of storage to subgrids, in order to reinforce the grid and keep market access open, and for pre-detection of grid bottlenecks when integrating RE generation and sector-coupling.

2 Analysis and Presentation of Monitoring Data are subject to a complementary document

3.4 Spatial Aggregation for Larger Areas

Combining data from different subgrids in a common larger area is straightforward for total generation yield Y_G^* and total load yield Y_L^*. With the subgrid yields normalized to their subgrid nominal powers P_i^0, equivalent to the power-flows, the overall yields Y_{AREA} can be aggregated

$$Y_{Area}^* = \frac{1}{P_{Area}^0} \sum_i {}^{Y_i}\!/_{P_i^0}$$

by re-normalization to the nominal power P_{Area}^0 of the larger area, thus providing the reference for surplus-energy and energy-balance ratios.

When coupling subgrids, the aggregation of net generation Y_{NG} and total load Y_{NL} yields only represent the surplus-generation/deficit-load within the subgrids. These yields, representing averages of directed power-flows, can not reflect the balancing of surplus and deficit between different subgrids. Instead, these balancing effects are resulting as difference against the yields $Y_G^* = \frac{1}{P_{Area}^0} \sum_i (Y_{TU,i}/P_i^0)$ and $Y_L^* = \frac{1}{P_{Area}^0} \sum_i (Y_{FU,i}/P_i^0)$ summed up from utility-coupled surplus and deficit shares of subgrids in the aggregated area. Comparison with net generation power P_{NG}^* and net load power P_{NL}^* is then reflecting improved direct and buffered self consumption in the aggregated area, due to balancing of surplus and deficit between different subgrids.

In Annex C, the recursive structure for cascaded area storage shows the correspondence, with net generation power P_{NG}^* and net load power P_{NL}^* resulting in the same way as for a subgrid from independent measurement of utility interface and storage power in the aggregated area. The directed power-flows re-appear in the same structure reproduced, allowing for an area view, employing the same performance evaluation and analysis tools as for storage systems in subgrids.

4 Conclusions

With the guidelines for assessment of photovoltaic plants, previously extended for AC coupled photovoltaics, this addendum allows to cover AC coupled storage systems as well, in the performance monitoring framework established.

In analogy to the flows in DC-coupled PV systems, monitoring is separating interconnection side storage flows from subgrid balancing storage flows and provides an unified data structure for analysis of storage performance in the system context, flexibility provision and accounting/contracting of ancillary services.

The power flow decomposition used, is recursively applicable for larger grid areas while employing unified performance evaluation and analysis of operation data in normalized form. Temporal and spatial aggregation allow to cover long-term progress in grid integration of photovoltaics and sector coupling towards climate neutrality, as needed for statistical follow-up.

Related Documents

[1] Blaesser,G., D.Munro : Guidelines for the Assessment of Photovoltaic Plants, Document A - Photovoltaic System Monitoring. Report EUR 16883 EN, JRC Institute for Systems Engineering and Informatics 1995

[2] Blaesser,G., D.Munro : Guidelines for the Assessment of Photovoltaic Plants, Document B - Analysis and Presentation of Monitoring Data. Report EUR 16339 EN, JRC Institute for Systems Engineering and Informatics 1995

[3] Blaesser,G., J.Sachau : Access to Design and Operation Experience in the European PV Monitoring Database. 2nd World Conference Photovoltaic Solar Energy Conversion, Vienna 1998

[4] Sachau,J.: Updating of Guidelines for the Assessment of Photovoltaic Plants. Technical Note No. I.99.157, JRC Environment Institute 1999

List of abbreviations and definitions

SCP	storage connection point
UIP	utility interconnection point
PV	photovoltaics
RE	renewable energies
DC	direct current
AC	alternative current

List of figures

Annexes

Annex 1. Power-Flow Mapping

Arranging the power-flow composition in matrix form

$$\begin{pmatrix} P_{G\_U} \\ P_{G\_S} \\ P_{S\_U} \\ P_{U\_S} \\ P_{S\_L} \\ P_{U\_L} \end{pmatrix} = \begin{bmatrix} 1 & -1 & & & & \\ & 1 & & & & \\ & & 1 & & -1 & \\ & -1 & & 1 & & \\ & & & & 1 & \\ & & & & -1 & 1 \end{bmatrix} \cdot \begin{pmatrix} P_{NG} \\ (P_{NG} - P_{TU})^{+} \\ P_{FS} \\ P_{TS} \\ (P_{FU} - P_{NL})^{-} \\ P_{NL} \end{pmatrix}$$

allows for verification that this mapping is reversely unique. The inverse mapping

$$\begin{pmatrix} P_{NG} \\ (P_{NG} - P_{TU})^{+} \\ P_{FS} \\ P_{TS} \\ (P_{FU} - P_{NL})^{-} \\ P_{NL} \end{pmatrix} = \begin{bmatrix} 1 & 1 & & & & \\ & 1 & & & & \\ & & 1 & & 1 & \\ & 1 & & 1 & & \\ & & & & 1 & \\ & & & & 1 & 1 \end{bmatrix} \cdot \begin{pmatrix} P_{G\_U} \\ P_{G\_S} \\ P_{S\_U} \\ P_{U\_S} \\ P_{S\_L} \\ P_{U\_L} \end{pmatrix}$$

is suitable for verification of the energetic balance. Positive and negative parts of averaged storage power-flows

$$\begin{aligned} (P_{NG} - P_{TU})^{+} = P_{G\_S} \quad & and \quad -(P_{NG} - P_{TU})^{-} = -P_{S\_U} \\ -(P_{FU} - P_{NL})^{-} = -P_{S\_L} \quad & and \quad (P_{FU} - P_{NL})^{+} = P_{U\_S} \end{aligned}$$

deliver the total sum of power components

$$(P_{NG} - P_{TU}) + (P_{FU} - P_{NL}) = P_{G\_S} - P_{S\_U} - P_{S\_L} + P_{U\_S}$$

or

$$(P_{NG} + P_{FU}) - (P_{TU} + P_{NL}) = P_{TS} \; - P_{FS}$$

to be compared with the power-flows to and from storage.

Annex 2. Parameters Recorded

Following the header record, the results of a recording period are forming a data group, with comma used as separator and data records in sequence of their acquisition, i.e. with increasing time-stamps. Further information and comments can be added following a '%' separator.

%% HEADER RECORD :

- [Distribution System Operator] , [Country]
- [Monitoring/System Operator] , [Storage System-Name] , [Storage Connection Point] , [WGS-latitude] , [WGS-longitude]
- [Storage Type] , [nominal power] , [nominal energy storage depth]
- [Utility Interconnection Point] , [nominal power] , [WGS-latitude] , [WGS-longitude]
- [Date] , [start-time] , [time-span]

Primary three phase measurements of active and reactive powers $P_{I \ldots III}$ and $Q_{I \ldots III}$, typical per grid-period, can optionally also be recorded, e.g. if ancillary services like phase-balancing and reactive power compensation shall be monitored.

%% PRIMARY POWER RECORDS :

- STORAGE CONNECTION RECORD :
  [time-stamp] , 'SCP' , [$P_{S,I}$] , [$P_{S,II}$] , [$P_{S,III}$] , [$Q_{S,I}$] , [$Q_{S,II}$] , [$Q_{S,III}$]
- UTILITY INTERCONNECTION RECORD :
  [time-stamp] , 'UIP' , [$P_{U,I}$] , [$P_{U,II}$] , [$P_{U,III}$] , [$Q_{U,I}$] , [$Q_{U,II}$] , [$Q_{U,III}$]
  ...

%% DIRECTED FLOW RECORDS (three-phase active power average over period):

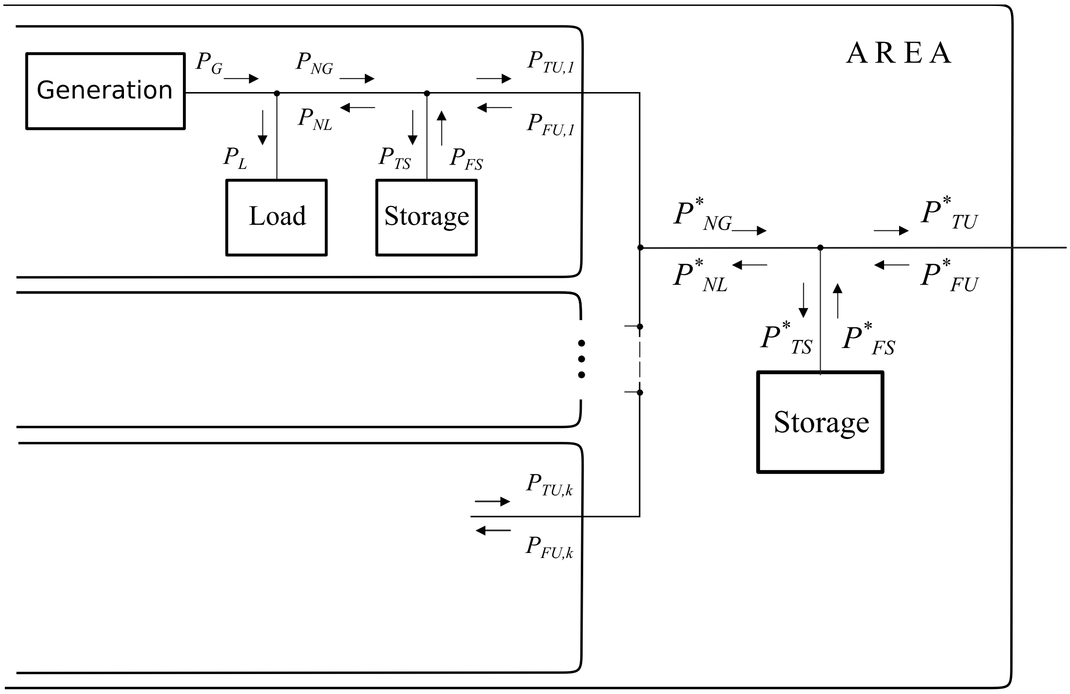
- POWERFLOW RECORD :
  [time-stamp] , 'PF' , [period] , [P_{G_S}] , [P_{S_L}] , [P_{G_U}] , [P_{S_U}] , [P_{U_S}] , [P_{U_L}]
  ...

%% FREQUENT RECORDS :

- TOTAL GENERATION RECORD : or TOTAL LOAD RECORD :
  [time-stamp] , 'G' , [period] , [P_G] [time-stamp] , 'L' , [period] , [P_L]
  ...
- STORAGE TYPE SPECIFIC RECORD : % for batteries with [Storage Type]='SB'
  [time-stamp] , 'SB' , [period] , [U_{Batt}] , [I_{Batt}] , [Temp]
  ...
- EVENT RECORD :
  [time-stamp] , 'E' , [event-specifier] , [event specific data]
  ...

Annex 3. Recursive Structure with Cascading Area Storage

Figure 3. Cascading Structure of Storage in Grid-Areas



Source: JRC elaborations 2020

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