ADVANCED PERFORMANCE MONITORING SYSTEM FOR IMPROVED RELIABILITY AND OPTIMIZED LEVELIZED COST OF ELECTRICITY

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ABSTRACT: The key factor that will enable and enhance the further increase of the uptake of photovoltaic (PV) technology globally, is the reduction in PV electricity costs by increasing the lifetime output of PV systems. This can be achieved by improving the reliability and service lifetime performance through constant, solid and traceable PV plant monitoring of installed systems. In this way, the investment cost, levelised cost of electricity (LCoE) and in general PV competitiveness can be enhanced positively. It is with this background that the project "Innovative Performance Monitoring System for Improved Reliability and Optimized Levelised Cost of Electricity" (IPERMON) funded by the SOLAR-ERA.NET Transnational Calls PV3 and CSP3, has been initiated between Gantner Instruments (GI) GmbH and the PV Technology Laboratory of the University of Cyprus (UCY), in order to develop an innovative monitoring system with enhanced capabilities, far beyond the state-of-the-art. The proposed monitoring system will be capable to detect performance losses and failures, determine the degradation rate and provide accurate hourly and day-ahead power production forecasts. The scope of this work is to present the main scientific, technological and commercial objectives of the project in the field of PV performance monitoring systems and to present first results for the formulation and benchmarking of innovative guidelines and algorithms for the detection and diagnosis of performance losses, degradation and failures.
Keywords: c-Si, degradation, forecasting, energy performance, lifetime, PV system.

1 INTRODUCTION

A key factor that will enable the further increase of the uptake of photovoltaic (PV) technologies is the reduction of PV electricity costs by increasing the lifetime output. In particular, this can be achieved by improving the reliability and service lifetime performance through constant, solid and traceable PV plant monitoring of installed systems. In this respect, safeguarding the optimal operation of PV systems directly impacts positively the investment cost, levelised cost of electricity (LCoE) and in general the technological competitiveness.

A main challenge in the quest for ensuring quality of operation especially for grid-connected PV systems is to safeguard reliability and optimal performance by identifying and quantifying accurately the factors behind the various loss mechanisms, minimising them by best design practice, while also detecting and diagnosing potential failures at early stages or before occurrence, through robust monitoring, fault detection and preventive maintenance.

At present, the most common guidelines or standards for PV system performance monitoring include the IEC 61724 standard [1], the guidelines of the European Joint Research Centre in Ispra, Italy [2-3] and the National Renewable Energy Laboratory (NREL) [4]. In addition, many academic institutions and organisations are particularly active in the development of sophisticated failure detection routines (FDR), degradation rate determination and accurate forecasting methodologies that are necessary for improved production [5-9].

At the moment, as most approaches for performance loss and failure identification are yet at an initial research stage and not fully tested and verified on a large amount of field data, there is as yet no complete monitoring platform for investors and in general end users to assess and diagnose performance issues of PV systems. As a result, there is a strong market need for a unified independent baseline platform for effective and automated PV plant management, which will be vendor-independent, and that will offer reduced risk for PV plant owners, preventive maintenance and improved financial key performance indicators (KPI) for investors.

The purpose of this work is to present the main scientific, technological and commercial objectives of the IPERMON project in the field of PV performance monitoring systems and to present first results for the formulation and benchmarking of innovative guidelines and algorithms for the detection and diagnosis of performance losses, degradation and failures. The end-product of the project will be an advanced monitoring system, which will act as a high level watchdog in ensuring reliability and operational quality of PV power plants and eventually yielding increased lifetime output.

2 PROJECT WORK PLAN

The project will be executed by a transnational consortium from two countries, Gantner Instruments (GI) GmbH and the PV Technology Laboratory of the University of Cyprus (UCY) and the duration is 36 months. More specifically, the methodology and technological process that will be utilised for this work includes the following steps:

1) Analytical review and benchmarking of data acquisition practices and guidelines.
2) Development of failure detection routines (FDR) to analyse sub- five minute meteorological and

PV operational data-sets against profiles of different failures and comparisons with predefined profiles (energy loss, deviation, behavioural change, spatial/neighbour PV array dimension, duration and modelled desired output correlations) of common failure modes.

3) Application of filtering steps and advanced statistical analysis techniques such as the Autoregressive Integrated Moving Average (ARIMA), regression model with ARIMA (regARIMA), robust Principal Components Analysis (rPCA) [10-13] and Loss Factors Model (LFM) [14] for the assessment of data acquisition quality, outages and performance assessment.
4) Application of trend-extraction methods for the algorithm formulation of performance losses, failures and long term degradation.
5) Implementation of advanced pattern classification and recognition algorithms employing artificial neural networks (ANN) for the production forecasting of grid-connected PV systems.
6) Emulation of failures and validation of the algorithms.
7) Use of web-based application programming to integrate the developed algorithms to an advanced web-portal.
8) Testing of the performance and accuracy of the tool against real operating PV systems.

The developed monitoring solution will be hosted as a plug-in to the already implemented web-portal of GI (see Fig. 1).

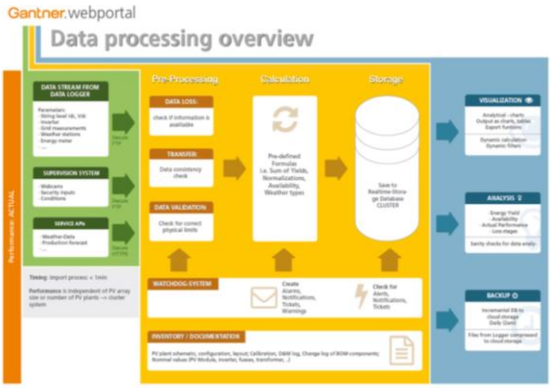


Figure 1: GI webportal functionality outline.

3 METHODOLOGY

3.1 Data-acquisition guidelines

Data-acquisition through advanced monitoring systems is necessary to measure and assess the performance of PV systems and also to identify design faults and failures. For many large scale grid-connected PV systems, performance analysis on acquired data is further performed in order to identify and prevent economic losses due to operational problems and timely detection.

The first part of the project is the formulation of monitoring guidelines on the acquisition and analysis of PV performance data-sets for the development of innovative algorithms for the diagnosis of performance losses and FDR. In particular, it is imperative that in order to detect failures and performance losses the data-sets sampled and acquired will be at a high resolution (1-5 minutes), thereby extending the measurement requirements beyond the recommendations of the IEC 61724 standard [1], for measurement, data exchange and performance analysis of PV systems. Typical measurements acquired at the developed testing sites will include with respect to the meteorological data, the total irradiance in the plane of the array (E_{POA}), ambient temperature (T_{amb}), module temperature (T_{mod}), wind speed (W_s) and wind direction (W_d). Additionally, with respect to the PV operational system side data acquired include (DC voltage, current and power) and utility side (AC grid voltage, current, power, outage duration period). Figure 2 shows an outline of the proposed advanced monitoring system installation including sensors, data acquisition devices, storage systems and portals for large scale PV plants.

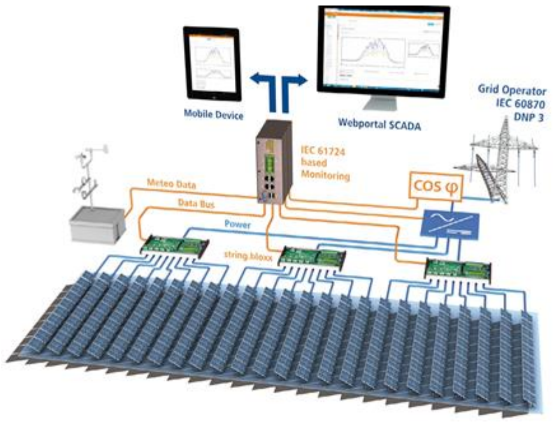


Figure 2: Outline of the advanced monitoring system installation for large scale PV plants.

In addition, an important consideration before analysing any time series data set is the quality of data. In this sense, the service time i.e. the duration of monitoring without outages, is an important parameter to be known before commencing the analysis of the data and quantification/qualification of losses. In particular, attention should be given to the following details [4]:

- The data must be carefully examined for missing or erroneous data.
- Inconsistencies in the frequency of data collection and/or duplicate records should be identified and addressed.
- Nonzero irradiance and electrical measurements that might affect the expected or measured energy should be removed. Night time data should only be used for meteorological data such as temperature, precipitation and windspeed analysis.

Throughout the progress of the project different methods will be investigated on how to analyse the time series for outages and what data filtering techniques and algorithms can be applied to reconstruct the time series. The influence of outages on the degradation rate estimation and energy yield production will also be studied.

3.2 Degradation rate determination

Based on previous work performed at the UCY in the field of degradation rate determination [10-13], the developed algorithms will make use of data sets acquired for the irradiance, ambient/module temperature and DC/AC maximum power (P_{mp}), in order to first calculate the performance ratio. Once the performance ratio (PR) is calculated on a daily and monthly basis then suitable statistical techniques such as seasonal autoregressive integrated moving average (SARIMA) and principal component analysis (PCA) are applied on the implemented time series. The following flow chart describes the general principle of the degradation rate algorithms (see Fig. 3).

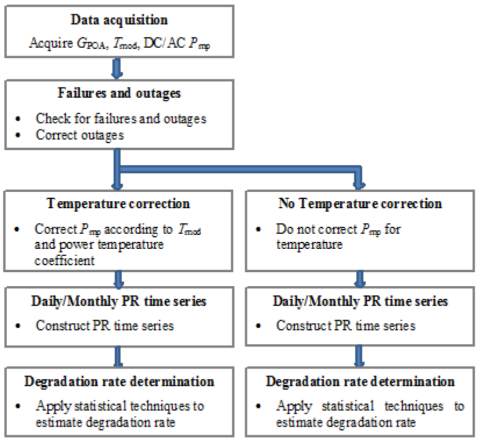


Figure 3: Degradation rate determination algorithm procedural flow chart.

3.3 Failure detection routines (FDR)

Based on the proposed guidelines different algorithms will be developed in order to identify and quantify system performance losses due to thermal and irradiance behaviour, soiling, shading, string mismatch, bypass diode effects, inverter failures and insulation faults, non-optimal maximum power point tracking (MPPT) and unexpected trends. The algorithms will perform real-time comparisons against known failure profiles and performance effects, threshold levels and modelled expected performance in order to first identify the loss and then quantify the effect.

More specifically, the FDR will operate on acquired data sets by producing the daily power production profile which will be tested against known failure/malfunction profiles, determining thus possible causes. The important parameters considered for the verification of the failure include:

- Comparison with simulated energy yield models.
- Magnitude of the fault.
- Parameters affected and correlated with the fault.
- Duration of the fault (day to month).
- Cross reference with other healthy parameters.

For the development of the FDR the system will comprise of the failure detection tool and the failure profiling and footprint methods. The routines will evaluate patterns of energy loss by creating profiles and comparisons with predefined profiles of frequently known failures such as hot spots, bypass diodes, inverter faults, grid outages and others. The operational verification of the algorithms will be performed on an experimental test-setup at the UCY and the outdoor test facility (OTF) of GI against emulated faults and measured performance effects (see Fig. 4).

Figure 4: Outdoor test facilities of a) GI in Tempe, Arizona and b) UCY in Nicosia, Cyprus.

The flow chart below describes the procedural flow of the FDR (see Fig. 5).

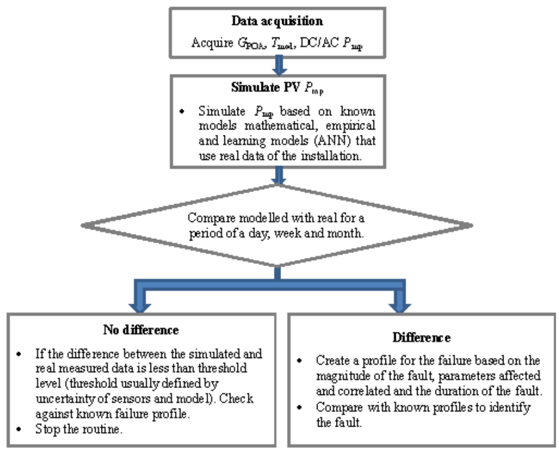


Figure 5: FDR procedural flow chart.

3.4 Integration of the Loss Factors Model (LFM) into the analysis

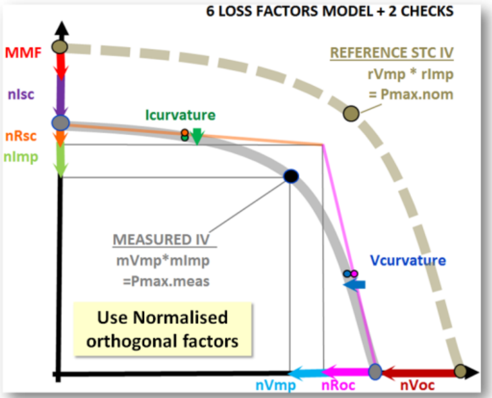
The Gantner Instruments/SRCL Loss Factors Model (LFM) (see Fig. 6) is being integrated into this analysis to provide an even better understanding of the performance and degradation modes.

The LFM has 6 normalised orthogonal parameters associated with I_{SC}, R_{SC}, I_{MP}, V_{MP}, R_{OC} and V_{OC}. The product of all 6 gives the PR_{DC}. Using normalised coefficients means:

- An easy sanity check for bad data if not ~1.
- It is easy to tell good from bad values e.g. 98% or 90%.
- It can differentiate PV technologies – e.g. thin Film usually has a higher loss due to R_{OC} (from thin conductive oxide resistivity).

The system can plot LFM values vs. the parameters below to determine the following [15]:

- vs. Time → Degradation or annealing rates
- vs. Irradiance → Low light performance behaviour
- vs. Module temperature → Thermal coefficients



MMF	Module Mismatch factor – Spectral	
nI_{SC} (U)(T)(S)(D)	Loss to $I_{SC.MEASURED}/I_{SC.EXPECTED}$	Corrections: (U)ncorrected (T)emperature (S)pectral correction (D)irt
nR_{SC}	Loss due to R_{SC} (~R_{SHUNT})	
nI_{MP}	Loss near P_{MAX} to I_{MP}	
nV_{MP}	Loss near P_{MAX} to V_{MP}	
nR_{OC}	Loss to R_{OC} (~R_{SERIES})	
nV_{OC} (U)(T)	Loss to $V_{OC.MEASURED}/V_{OC.EXPECTED}$	

Figure 6: Gantner Instruments/SRCL LFM.

Figure 7 analyses degradation rates as functions of LFM coefficients for a CIGS module in Arizona. Most degradation rates reported in the literature are only for standard test condition (STC) corrected efficiency which is limited by any inaccuracy in the I_{SC} value (this could be caused by soiling, snow, spectral, angle of incidence or irradiance sensor changes with time). Because the LFM separates out the degradation into almost independent coefficients the cause of the degradation can be seen – Figure 7 clearly shows the residual (measured – predicted) degradation is dominated by nV_{OC} , nI_{MP} and nR_{SC} with a smaller drop in nR_{OC}.This implies that the shunt resistance is falling as is the current near I_{MP}.

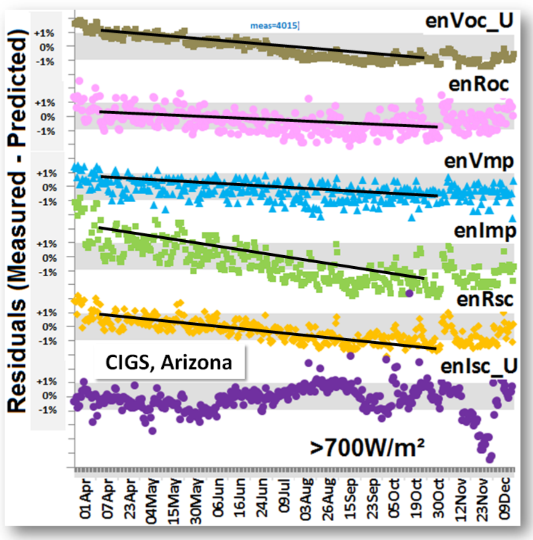


Figure 7: Degrading performance of a CIGS module in Arizona analysed with the LFM.

4 RESULTS

Routines and algorithms for performance loss rate estimation due to high temperature, soiling and failure detection of modules/arrays and sensors have already been implemented by the PV Technology Laboratory UCY [10-13]. As a snapshot of the undertaken work, the results of the degradation rates of different systems applying the developed long term degradation algorithms and the results of indoor techniques using a solar simulator and electroluminescence (EL) imaging, demonstrated that the estimated annual PLR of crystalline Silicon (c-Si) arrays with no visible defects were comparable with outdoor time series analysis and indoor STC maximum power determination results. Especially strong agreement was exhibited between STC and regARIMA modelling results (see Fig. 8) [10]. Some of the higher degradation rates that have been observed through the indoor STC testing were attributed to failures as also identified by EL imaging.

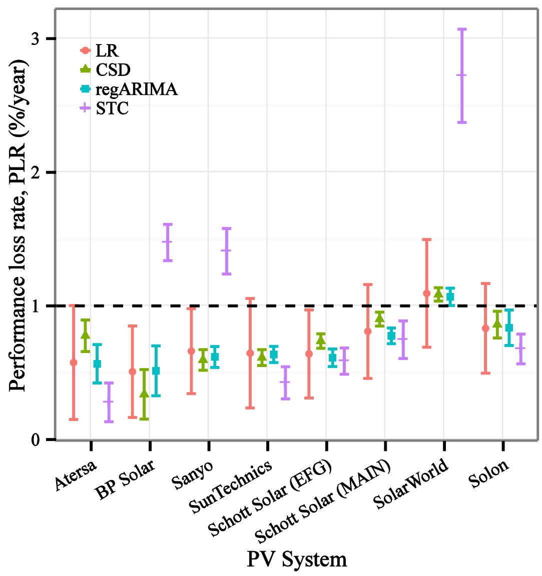


Figure 8: Annual performance loss rates evaluated through outdoor time series analysis for the evaluation period June 2006 – October 2014 and indoor testing at STC. The 1 %/year line is used as a visual aid [10].

Finally, preliminary FDRs developed to detect Potential Induced Degradation (PID), string and inverter defects, shading and hot spots are currently tested and benchmarked on historical data sets acquired for different technology PV systems. First results showed that the FDRs can detect malfunctions in the normal operation of PV systems. More specifically, the routine recognized that the power loss (difference between the measured and modelled power) was outside predefined limits and suggested an inverter or grid outage failure (see Fig. 9). As the routines are yet in the initial development stage an important step to ensure correct detection of specific faults is to include predefined failure patterns. Depending on the degree of coincidence between the failure profile and the predefined profiles along with inputs from other measurements the routines will be able to distinguish amongst the failures.

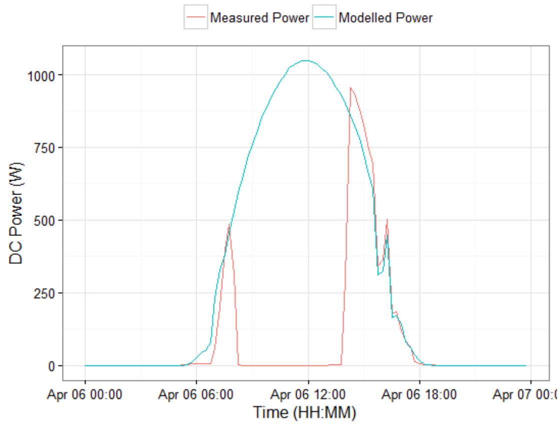


Figure 9: Measured and modelled power of a PV system during the FDR testing phase.

5 CONCLUSIONS

In this work the main scientific, technological and commercial objectives of the project "Innovative Performance Monitoring System for Improved Reliability and Optimized Levelised Cost of Electricity" (IPERMON) funded by the SOLAR-ERA.NET Transnational Calls PV3 and CSP3, in the field of PV performance monitoring systems were presented.

Specifically, the expected results of the proposed work, which include the development of performance loss, failure and degradation rate detection algorithms, improved forecasting and a reliable solution for PV monitoring, will create new knowledge which will advance the field of PV reliability. The advanced monitoring system, which will be the main outcome of this project, will offer reduced risk for PV plant owners, preventive maintenance and improved financial KPI for investors.

Finally, it is anticipated that the successful completion of the project will push a highly innovative end-product straight to the market that will act as a high level watchdog for ensuring reliability and operational quality of PV power plants.

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7 REFERENCES

[1] IEC 61724 Standard, Photovoltaic system performance monitoring guidelines for measurement, data exchange and analysis, IEC 1998.

[2] G. Blaesser and D. Munro, Guidelines for the assessment of photovoltaic plants Document A Photovotlaic system monitoring, Commission of the European Communities, Joint research Centre, Ispra, Italy, EUR 16338 EN, 1995.

[3] G. Blaesser and D. Munro, Guidelines for the assessment of photovoltaic plants Document B Analysis and presentation of monitoring data, Commission of the European Communities, Joint research Centre, Ispra, Italy, EUR 16339 EN, 1995.

[4] S. Kurtz, E. Riley, J. Newmiller, T. Dierauf, A. Kimber, J. McKee, R. Flottermesch and P. Krishnani, Analysis of photovoltaic system energy performance evaluation method, NREL Technical Report, NREL/TP-5200-60628, 2013.

[5] S. Stettler, P. Toggweiler, E. Wiemken, W. Heydenreich, A. C. de Keizer, W. van Sark, S. Feige, M. Schneider, G. Heilscher, and E. Lorenz, Failure detection routine for grid-connected PV systems as part of the PVSAT-2 project, *in: 20th EUPVSEC*, 2005, pp. 2490- 2493.

[6] A. Drews, A. C. De Keizer, H. G. Beyer, E. Lorenz, J. Betcke, W. Van Sark, W. Heydenreich, E. Wiemken, S. Stettler, and P. Toggweiler, Monitoring and remote failure detection of grid-connected PV systems based on satellite observations, *Solar Energy*; 2007; 81: 548-564.

[7] T. Oozeki, T. lzawa, K. Otani, and K. Kurokawa, An evaluation method of PV systems. *Solar Energy Materials and Solar Cells*; 2003; 75: 687-695.

[8] S. Mau and U. Jahn, Performance analysis of grid-connected PV systems, *in: 21st EUPVSEC*. 2006, pp. 2676-2680.

[9] S. J. Ransome, J. H. Wohlgemuth, S. Poropat, and E. Aguilar, Advanced analysis of PV system performance using normalised measurement data, *in: 31st IEEE Photovoltaic Specialists Conference*, 2005, pp. 1698-1701.

[10] A. Phinikarides, G. Makrides and G. E. Georghiou, Estimation of annual performance loss rates of grid-connected photovoltaic systems using time series analysis and validation through indoor testing at standard test conditions, *in: 42nd IEEE Photovoltaic Specialists Conference*, 2015, pp. 1-5.

[11] A. Phinikarides, G. Makrides, M. Schubert and G. E. Georghiou, Analysis of photovoltaic system performance time series: seasonality and performance loss Renewable Energy, *Renewable Energy*; 2015; 77: pp. 51-63,

[12] G. Makrides, B. Zinsser, M. Schubert and G. E. Georghiou, Performance loss rates of different photovoltaic technologies, *Solar Energy*; 2014; 100: 28-42.

[13] A. Phinikarides, N. Kindyni, G. Makrides and G. E. Georghiou, Review of photovoltaic degradation rate methodologies, Renewable and Sustainable Energy Reviews, 2014; 40: 143-152.

[14] J. Sutterlueti, S. Ransome, R. Kravets and L. Schreier, Characterising PV modules under outdoor conditions: What's most important for energy yield, *in: 26th EUPVSEC*, 2011, pp. 3608-3614.

[15] S.Ransome and J. Sutterlueti, Degradation Analysis of PV Technologies Using NREL and Gantner Instruments Outdoor Data, *in: 43nd IEEE Photovoltaic Specialists Conference*, 2016.