PVSAT-2: INTELLIGENT PERFORMANCE CHECK OF PV SYSTEM OPERATION BASED ON SATELLITE DATA

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ABSTRACT: Early detection of faults in grid connected PV systems increases efficiency, reliability and cost-effectiveness. However, due to the variability of solar irradiation and therefore of the energy yield these faults are difficult to detect for system operators. The European PVSAT-2 project will set up a fully automated performance check for grid connected PV systems. A central knowledge-based decision making system will analyse the performance of the PV system on a daily basis, and will be able to detect system failures and its possible causes. The actual system power output will be measured by a low cost hardware device and communicated to the central decision making system. The calculation of the reference yield is based on solar irradiance data derived from satellite images combined with additional ground data where possible. Improvements of the irradiance accuracy, achieved within this project, directly result in a higher accuracy of the overall scheme and thus in an earlier fault detection.
In our paper we will present the structure of the PVSAT-2 performance check, improvements of the irradiance calculation scheme with a detailed error assessment, and the development of the tool for automated fault detection.
Keywords: small grid connected PV, quality control, performance check, yield optimization

1 INTRODUCTION

A large number of small grid connected PV systems is in operation in Europe today, and a strong increase is expected for the near future. Today, the installed PV power of small systems increases with remarkable rates in some countries, e.g. with some 10 MW_{peak} per year in Germany. Generally, these PV systems in a power range from 1 to some 10 kW_{peak} do not include any long term surveillance mechanism. As most system operators are not PV specialists, system faults (component failures) or decreasing performance (e.g. due to increasing shading by growing vegetation) will not be recognized and the individual plant owner will encounter financial losses. Regarding the increasing pay-back rates for PV energy (0.5€/kWh in Germany since spring 2000, similar initiatives are foreseen in other European countries), the cost argument becomes more and more important for both plan owners as well as for the PV industry.

Therefore, there is a need for methods which allow for a cheap and reliable performance check of the power production of grid connected PV systems. The PVSAT-1 procedure [1] addresses this issue by providing operators with a system specific monthly reference yield. This reference yield is determined by a generic system model that uses hourly irradiance data from satellite images and individual system descriptions as input. A field test of the PVSAT-1 procedure proved the value of the method in practice, but also showed a limited commitment of clients to a regular comparison of measured and reference yield [2]. Furthermore, it showed that the accuracy of the irradiance input was the limiting factor for the overall accuracy [2, 3]. In the currently ongoing PVSAT-2 project the performance check procedure will be further improved:

- A central knowledge-based decision making system will analyse the performance of the PV system on a daily basis, and will be able to detect system failures and its possible causes ('footprint' method).
- A low cost hardware device will be integrated into the PV system for automated measurements and communication to the central decision making system. This will increase the reliability of the yield measurements and make the PVSAT-2 application more easy to use.
- The accuracy of the irradiance data will be further improved. With this aim additional online ground data will be combined with satellite data using a kriging-of-the-differences interpolation. This method also supplies information on the expected quality of the derived irradiance values, thus supporting the decision making system. Furthermore, new developments in the field of meteorological satellites and an improved diffuse irradiance model will be integrated into the procedure.
- The calculation scheme for the behavior of modules and MPP-tracking will be further improved. Special attention will be paid to the development of models for thin film technologies. Results of this subtask are given in [4].

These additions will improve the accuracy, speed of error detection and userfriendlyness of the procedure. The procedure will be validated in a one-year field test on PV systems in Germany, the Netherlands and Switzerland.

In our paper we will present the structure of the PVSAT-2 performance check, the development of the error detection routine and first results of the improved irradiance calculation. Additional information can be found on http://www.pvsat.de.

2 PVSAT2 PROCEDURE

The PVSAT-2 procedure consists of the following

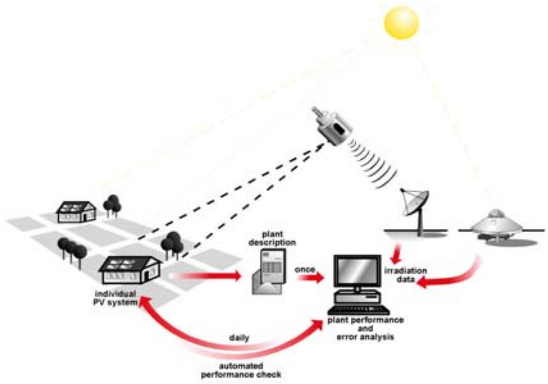

Figure 1: Schematic overview on the PVSAT2 procedure

steps that are illustrated in Fig. 1:

1) The actual power output of a PV system is automatically recorded at the PV system and transferred to a central server.
2) The reference yield is calculated at the central server: Solar radiation is determined from METEOSAT images on an hourly basis. To refine this data set, ground measurements of solar irradiance recorded hourly at weather stations will be interpolated by kriging across Germany. Based on the derived irradiance values, an individual yield calculation for a PV system will be performed daily by a simulation model. The simulation model uses preliminary information supplied by the operator about the PV modules: orientation, inclination and configuration of the modules, type of inverter used, and a horizon line.
3) To detect system errors, the central decision making system will compare actual and reference yield daily. A fully automated error detection routine will search for causes of malfunctions.
4) The owners of the PV system are informed about system failures and probable causes for the malfunction.

3 SOLAR IRRADIANCE FROM SATELLITE DATA AND GROUND STATIONS

The information on solar irradiance will be derived form satellite data and measurements from ground stations rather than from on-site measurements. This solution has the advantage of avoiding extra costs and additional maintenance efforts for irradiance sensors.

In the PVSAT-1 project [2] it was shown that the accuracy of the overall procedure is mainly determined by the accuracy of the irradiance calculation scheme. Improvement of the irradiance accuracy will therefore directly result in a higher accuracy of the overall scheme and thus in an earlier fault detection.

3.1 Improvement of satellite derived irradiance.

The derivation of the surface irradiance from the satellite measurements is based on an enhanced version of the semi-empirical Heliosat method [5, 6]. In a first step information on clouds is extracted from the satellite images and related to the transmissivity of the atmosphere. In a second step the clear sky irradiance is calculated for a given location and time. Finally, the clear sky irradiance is combined with the information on clouds for a given situation to infer the global surface irradiance.

For the calculation of the energy yield the global irradiance is converted to the module plane. The diffuse component is estimated using the model of Skartveit and Olseth [7] and the conversion to the tilted surface is done with the method of Klucher [8].

Currently the irradiance calculation is based on images of the geostationary satellite METEOSAT-7 with a temporal resolution of 30 min and a spatial resolution of 2.5 km x 4.5 km for central Europe. Data from this satellite were used for the error analysis in the following chapter.

For the operational service data from METEOSAT-8 will be used, which is the first of the new Meteosat Second Generation satellites. With METEOSAT-8 images with a spatial resolution of approximately 1km x 1.5 km will be available every 15 minutes. Furthermore the enhanced spectral resolution offers the possibility for an improved irradiance calculation scheme. The new clear sky module is based on the integrated use of a radiative transfer model [9]. The new calculation scheme allows for an improved modeling of the direct and diffuse components of the radiation, and thus for a more accurate derivation of the irradiance on a tilted plane. The improved model will be integrated in the operational PVSAT2 procedure.

3.1 Information on the accuracy of the satellite derived irradiance

The automated performance check provided by the PVSAT-2 service requires not only high-quality irradiance data input, but information on the accuracy of the input as well. This quality information is necessary to decide whether the difference between calculated and measured power output is caused by the uncertainty of the calculation of the power output or by system malfunctions.

A detailed two-dimensional error analysis was performed to distinguish meteorological conditions that correspond with different error levels. Two parameters were chosen to characterize situations with different levels of accuracy: sun elevation and spatial variability of the irradiance. For situations with inhomogeneous clouds, corresponding to a high variability in irradiance, the derivation of ground irradiance from satellite data is more difficult and larger errors are expected.

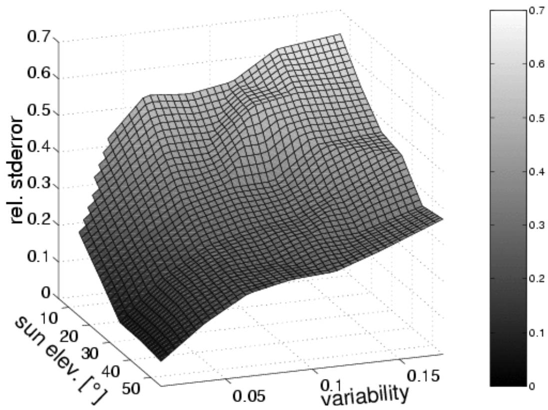

Figure 2: Relative stderror of the Heliosat method depending on the sun elevation and the variability.

The relative standard error of the Heliosat method for half hourly values is displayed over sun elevation and a variability index in Fig. 2. The accuracy of the Helisoat method shows a clear dependency on both parameters. Errors are high for low sun elevations, while for sun elevations above 20^o the standard error is below 40% for all situations. For situations with high irradiance, corresponding to sun elevations higher than 20^o and clear sky situations characterized by very low variability, there is a very high accuracy of the Heliosat method with errors smaller than 10 % .

Hence for clear sky conditions a fault diagnosis is possible within a few days after occurrence of the fault. Since these situations correspond to high power productions a fast detection of malfunctions of the PV system is most important. For less favourable conditions a longer evaluation period is necessary to reduce errors by averaging. However, as these conditions are related to modest energy production, energy losses in cases of a system failure are limited.

3.2 Combination of satellite and ground data

As stated before, improvement of the irradiance calculation is an important feature for an early fault detection. To achieve this aim the satellite-derived irradiance values are combined with additional data from ground stations.

With an relative rmse of 2 to 3% for daily values, pyranometer measurements are the most accurate way to determine irradiance. However, such ground data are only available from a small number of meteorological stations. The Heliosat method provides data on a very fine grid, but is less accurate. The advantages of both methods can be combined by first subtracting the Heliosat values from the ground measured values at the meteorological stations, then interpolating this difference to the location of the PV system and finally adding this correction to the Heliosat value at the location of the PV system. For the interpolation the kriging method which originates from the field of geostatistics [10] is used. Kriging uses information on the variability of the field to determine the optimal interpolation weights and to estimate the accuracy of the result.

The kriging-of-differences method has been cross-validated with 10 months of data from 34 ground stations in eastern Germany. A significant improvement is achieved for both daily and hourly irradiance values (Tab. 1). Furthermore, the actual accuracy is in good agreement with the predicted accuracy of the kriging-of-differences method.

The accuracy as a function of the value of the irradiation is investigated in Fig. 3. The largest improvement is obtained for low irradiation values where the Heliosat method shows a large relative rmse.

Table I: Relative rmse (%) of the Heliosat method, as found and as predicted by the kriging-of-differences method.

Time scale	*Heliosat*	*Kriging of Differences*	*Predicted rRMSE*
day	14.5	12.2	12.4
hour	26.3	24.3	24.5

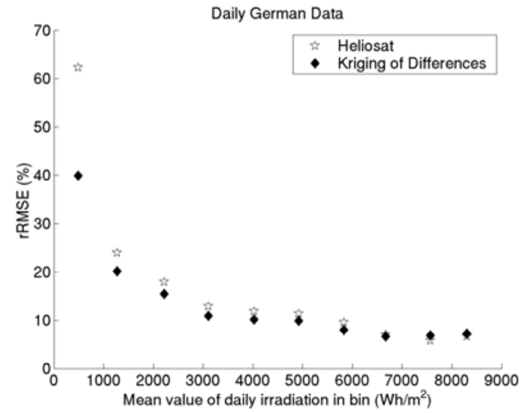

Figure 3: Accuracy of the Heliosat and the kriging of differences method for daily values as a function of irradiation.

4 AUTOMATED ERROR IDENTIFICATION

The basis for the automated error detection is the comparison of the expected and the monitored energy yield. The error detection tool combines two parallel approaches, focusing on different error types. Major energy losses are identified with the error detection routine, developed by Enecolo AG. With the ‘footprint algorithm’, developed by Fraunhofer-ISE malfunctions resulting in minor energy losses can also be detected and the most probable reason for the system failure is determined.

The interaction between the two approaches will be investigated during the test phase of the project.

4.1. Error detection routine

The error detection routine works on a daily base. If the difference between the monitored and the calculated daily energy sum exceeds the maximum assumed uncertainty of the calculated yield, the occurrence of a system failure is assumed..

To find the reason for the malfunction different aspects of the observed failure are investigated. These aspects are the daily and hourly energy loss, dependency on temperature and irradiance, frequency and time course of the energy loss, spatial dimension of the failure and probability of occurrence. The results of this analysis are compared to the characteristics of possible failures, that were specified in a predefined list. Thus the agreement of the given malfunction with a certain error profile is checked and the most probable error is determined.

In the subsection 3.3 it was shown that the uncertainty of daily irradiance sums and hence also the uncertainty of the derived power output can be large for single values of the daily irradiance sum, specially in the winter season with conditions of low irradiance. Therefore the error detection routine will mainly detect major energy losses.

4.2. Footprint algorithm for automated error detection

The footprint algorithm was developed to identify system malfunctions that are more difficult to detect, e.g. shading or inverter malfunctions. To detect these types of error an hourly resolution of the input data is required. Since hourly irradiance values may provided with large error ranges, a special statistical approach to reduce errors by averaging was applied.

The footprint method basically consists of two steps. In a first step the time series of monitored and calculated yield are prepared to extract error patterns. In a second steps the error patterns are compared to typical error patterns of selected system faults.

In order to prepare the signals, average values of $P^* \equiv P_{simulated}/P_{monitored}$ with corresponding error bars s_i^* are displayed over two parameters, the normalized power output $P_{monitored}/P_{installed}$ and the time (Fig. 3). The patterns are displayed as sample averages rather than as individual values to reduce the uncertainty of the input signal. Average values of three different time periods are considered (the past day, the last seven days and the last 30 days).

To reduce the signal to more simple error patterns 'error marks' $error_i^*$ are assigned to the intervals (Fig. 4). The error mark is set to one, if significantly less power is actually produced than simulated. If the monitored power production is within the error range of the simulated power production, $error_i^*$ gets the value zero.

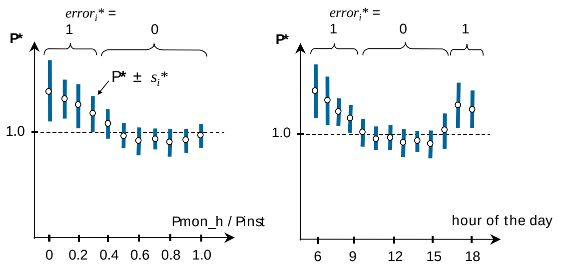

Figure 3 As an example, the sample averages P* are shown with their errors s_i^* in the $P_{monitored}/P_{installed}$ domain and in the time domain. The value of the corresponding error mark $error_i^*$ is also included.

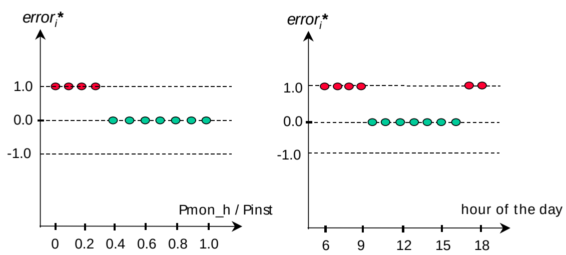

Figure 4 From the example shown in Fig. 3, the error pattern is extracted by displaying the values of the error marks as a function of the domain intervals.

The error patterns are then compared with pre-defined error patterns for specific system malfunctions. Probability weights are distributed according to the expected appearance of the error and the more the real system behaviour follows this specific error pattern, the higher will be the probability for this error.

In the list of typical predefined error patterns the following system malfunction are included:

- Different types of shading
- Power limitation for high power values
- Permanent power loss including string error detection

First tests with monitored and simulated data of three PV systems showed a reliable operation of the algorithm.

5 CONCLUSIONS

The procedure of the PVSAT-2 service has been presented. The improved irradiance calculation scheme including data from ground stations allows for an early detection of faults. Information on the accuracy of the irradiance data comprising different error levels for different meteorological conditions is an important input for the error detection routine.

With the error detection routine and footprint algorithm promising approaches were developed to detect system errors on the one hand and to distinguish between system errors on base of pre-defined footprint tables on the other hand.

The overall performance of the PVSAT-2 service will be evaluated in an one year test phase.

6 ACKNOWLEDGEMENTS

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