INTEGRATED CONCEPT FOR PV PLANT MONITORING AND MODEL BASED ANALYTICS

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ABSTRACT: Photovoltaic technology allows large scale investments in a renewable power-generating system at competitive LCOE and low environmental impact. Large scale PV installations operate in a highly competitive market environment where even small performance losses have high impact on profit margins. Therefore, operation at maximum performance is the key for long term profitability. This can be achieved by advanced performance monitoring and failure detection methodologies. Performance losses caused by instant failures or gradual degradations must be prevented by identifying the causes of failures in a quick and reliable manner. The identification of failures and root causes requires an integrated concept for plant monitoring and failure detection, which was realised as part of the Austrian OptPV4.0 research project. In this paper we present an integrated approach on model-based fault detection, diagnosis and prognosis for optimized maintenance activities based on typically available SCADA data. The failure detection and diagnosis capabilities were demonstrated in a case study based on six years of SCADA data from a PV plant in Slovenia. In this case study underperforming strings were detected reliably and possible root causes were identified. Overall, the integrated approach shall contribute to an efficient and long-term operation of photovoltaic power plants with a maximum energy yield and shall be applied within the OptPV4.0 research project for monitoring photovoltaic plants.

Keywords: Expert-System, PV System Modelling, Monitoring, One-Diode Model, Model-Based State Detection (Virtual Sensors), Physics of Failure, Condition -, Predictive- and Reliability-Based Maintenance

1 INTRODUCTION

Driven by global energy policies solar power has become one of the key sources for renewable energy and is the most attractive source of renewable power generation today. In 2019 solar power accounted for 48% of newly added net power capacity, which is more than all new capacities of fossil power combined and also almost twice as much as new wind power capacities. Solar power Europe reports that 2019 global capacity of installed solar power has reached a total of 630 GW [1]. This development is enabled and driven by dramatically decreased LCoE for solar power plants. Lazard [2] has found that the average LCoE for solar power plants have reached 40$/MWh which is significantly lower than LCoE of unsubsidised fossil and nuclear power plants and on the same level as wind power. The leading role of solar power in global electricity production is expected to be strengthened in the next years. Solar Power Europe estimates the global installed solar capacity will grow to a total of 1.2 TW until 2022. While this is a huge potential for solar power it also comes with increased cost pressure and a highly competitive market environment. Therefore, ensuring maximum performance is a requisite for securing profit margins and bankability of PV projects. In this environment optimized operation and maintenance (O&M) activities are one measure to maximize plant performance. Especially the importance of early detection of performance losses and initiation of targeted countermeasures becomes evident.

Today, modern PV power plants are typically equipped with a monitoring system aiming at collecting data from main components such as inverters, energy meters and meteorological sensors. Standards such as IEC 61724 [3] recommend data acquisition with a granularity of 15 min. This recorded data is typically used for the calculation of standardized performance indicators such as performance ratio or technical availability. Advanced sensing and monitoring methodologies are typically not implemented due to cost restrictions. However, the ability of accurate detection, diagnosis and prognosis of failures and degradation could significantly improve the efficiency of O&M activities, maximize performance and thus further reduce LCOE [4].

In this paper we present an integrated approach on fault detection, diagnosis and prognosis for optimized maintenance activities based on typically available SCADA data. The approach is based on two main concepts for building a digital representation of PV power plants:

- Implementing a one-diode model as reference for detection of abnormal behaviour
- Physics of failure modelling of relevant degradation mechanisms as functions of Environmental and Operating Conditions (EOC) for diagnosis and prognosis

2 BACKGROUND

This section provides an overview on maintenance strategies and associated information needs for successful implementation. First, we shortly introduce common maintenance strategies which are of relevance in the photovoltaic (PV) O&M. Second, we explain the background of physical simulation of PV power plant behaviour and the concept of physics of failure. These two main concepts are utilized in our combined process of failure detection, diagnosis and prognosis.

2.1 MAINTENANCE STRATEGIES

Maintenance strategies can be classified in corrective and preventive strategies. In a corrective maintenance strategy action is taken after a failure occurred. In contrast preventive maintenance strategies aim at preventing the occurrence of failures by taking action before a failure occurred and prolonging the residual lifetime. Preventive maintenance can be further classified in time based, condition based and predictive approaches. Time based preventive maintenance is a simple strategy where maintenance actions are scheduled periodically based on predefined intervals. Condition based maintenance can be applied in cases where component condition can either be measured directly (level of wear) or is linked to measurable factors like vibration which indicate component condition. This approach often requires signal processing and automated algorithms, which makes it a more cost intensive strategy. Predictive maintenance strategies employ prognostic models to estimate a residual lifetime and schedule maintenance activities accordingly. Applicability of maintenance strategies for individual components highly depends on the availability of relevant information for decision making. Our approach on failure detection and diagnostics delivers valuable information for the implementation of predictive maintenance strategies.

2.2 PHYSICS OF FAILURE

The concept of physics of failure assumes that damage of components is accumulated due to an irreversible change in the microstructure of the component subjected to specific load conditions [5]. The accumulation of damage takes place incrementally over the operational lifetime of the component, although the effect might not be visible until a failure occurs. Load conditions such as thermal, electrical or mechanical loads are directly induced by environmental and operating conditions of the system. By quantifying the incremental damage as a function of Environmental and Operating Conditions (EOC) it is possible to derive statements about the condition of a component with respect to specific failure modes. The first step towards physical damage models is an analysis of a component in terms of possible failure modes. In this context a detailed analysis of failure mechanisms in photovoltaic systems, and its subsystems were carried out [6]. Based on this analysis it can be said that inverters, rectifiers, bypass diodes, photovoltaic modules, cabling and ac circuit breakers are the most critical components in the whole system. In most cases there are different failure mechanisms for a component. An investigation of photovoltaic systems showed that wire bonding lift off and solder fatigue of power electronic devices as well as thermal aging of capacitors are seen as most probable failure mechanisms in inverters and rectifiers [7], [8]. Furthermore, failure mechanisms like delamination, backsheet cracking, cell cracks, potential induced degradation (PID), burn marks, disconnections of ribbons and defect bypass diodes are widely reported in photovoltaic modules [9]. The goal of this analysis is to find the physical mechanism which causes a specific failure. The focus of the analysis should be on components and failure modes which have a significant impact on the reliability and thus on the performance of a PV power plant. Once possible failure modes and physical root-causes are identified, the analysis focusses on load and environmental boundary conditions which promote the incremental accumulation of damage for each identified failure mode. In this context, it has been shown that temperature and thermal cycling are seen as most critical operation conditions for power electronic devices [10] and for photovoltaic modules, which in addition see humidity and solar radiation, especially UV radiation as critical damage drivers [11]. Based on the understanding of failure modes and corresponding damage drivers the physical damage models will be derived. These models describe the relation between EOCs as an input and the accumulation of damage kinetics as an output. Damage evaluation is performed by applying damage models to time series of load data over the operational lifetime of the PV power plant to deliver the rate of degradation. Subsequently, accumulating the degradation rate delivers the damage sum, indicating the amount of endurance, consumed for each failure mode due to exposure to the load history. Furthermore, critical load conditions are identified and understood in detail which in some cases allows to avoid damage promoting operating conditions.

2.3 SIMULATION

A digital representation of the expected photovoltaic system behaviour as a function of real irradiance and temperature conditions can be modelled by the so called “diode-models” of PV cells.

PV cells have a nonlinear current-voltage (I- V) characteristic curve which depends on the environmental conditions, such as the solar irradiation, ambient and module temperature. Different approaches of photovoltaic cell models are used to describe the real electrical behaviour of PV cells [12]. These can be classified in one- and two-diode models. Based on the one diode model, the output current of a PV cell can be modelled by considering the generated photocurrent I_{PH} and Shockley’s equation to describe the exponential electrical current-voltage I(U) characteristic of a p–n junction. In addition, the real electrical behaviour of the cells caused by its losses are described by serial (R_S) and parallel (R_P) resistances. The equivalent circuit of the one-diode model is shown in Figure 1.

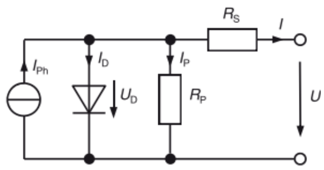

Figure 1: One-diode model of a PV cell [13]

The two-diode model is seen as more accurate in representing the behaviour of photovoltaic cells, especially for cells with higher bandgap energy, since the recombination rate at higher temperatures within the depletion region is also considered [14]. Due to more complex model parameters and the minimal performance advantage of the two-diode model, the modelling approach of this work is based on the one-diode model.

The output current of the photovoltaic cell of the one-diode model can be described by equation (**1**) and was modelled as a Simulink simulation [15].

$$I(U) = I_{PH} - I_D - I_P = \\ = I_{PH} - I_0 * \left(e^{\frac{U+I*R_S}{m*U_T}} - 1\right) - \frac{U + I * R_S}{R_P} \quad (1)$$

Where I_{PH} is the photocurrent, I_D the diode current, I_P the current through the parallel resistance, I_0 the diode reverse saturation current, U_T the thermal voltage, m an ideality factor, R_S the series resistance and R_P the shunt resistance.

Most of the above described model parameters are based on the datasheet values of the manufacturer and can be used straight forward for modelling. Only the series resistance R_S, and the shunt resistance R_P needs to be determined by a Newton Raphson iterative calculation

[15]. By performing this approach, equation (1) needs to be multiplied by U_{MPP} and solved by R_P.

By performing the iteration, the IV-curve will be emulated by varying the values I_{MPP} and U_{MPP} until the experimental maximum power equals the datasheet power. At this point in the IV-curve only one pair of values of R_P and R_S exists which represents the electrical behaviour of the photovoltaic cell at the maximum power point [15]. By using the determined R_P and R_S values and the one-diode model, one can calculate an accurate photovoltaic module current by using equation (**1**). A variation of the input parameters temperature and irradiance allows to model characteristic diagrams of maximum power, current and voltage at a wide range of load situations, as depicted in Figure 2.

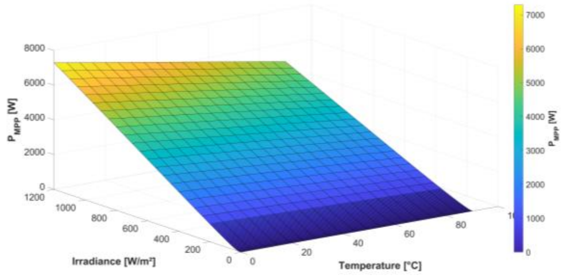

Figure 2: Characteristic diagram P_{MPP} f(T,G)

3 INTEGRATED CONCEPT OF MODEL-BASED MONITORING

The previously described concepts of simulation and physics of failure have individual advantages and limitations. The comparison of actual performance with the reference performance of a physical simulation by means of a one-diode model is an efficient method to detect abnormal operating behaviour. However, this method is not able to accurately diagnose the cause of abnormal behaviour. This information is needed to remedy the abnormal performance by initiating an efficient maintenance activity. On the other hand, the physics of failure approach identifies most likely failure modes but is limited in accurately predicting the time to occurrence of failure. Therefore, in this paper we propose a new concept which combines the advantages of both approaches as depicted in Figure 3.

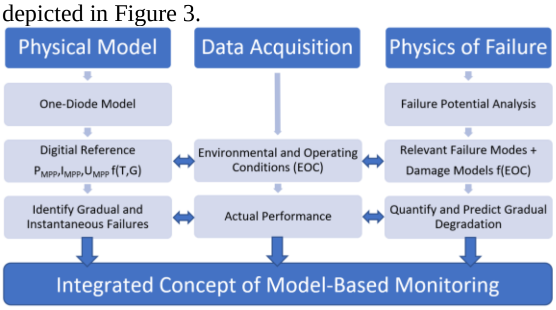

Figure 3: Integrated monitoring concept

Basis of this approach is the acquisition of EOC by means of available SCADA data. This data is used as an input in the physical model as well as in the physics of failure approach. While the physical model uses the real irradiance and module temperature as an input, the physics of failure models use individual inputs depending on the represented failure mode. By continuously comparing modelled performance with actual performance, we detect performance losses immediately. Once a performance loss and thus a possible failure is detected, we use the quantification of damage accumulation from the physical damage models to rank possible failure modes according to the risk of failure occurrence. With this combined concept we can reliably detect performance issues, diagnose corresponding failure modes and recommend targeted maintenance action.

4 MODEL BASED ANALYTICS

To demonstrate the failure detection and diagnosis ability of our approach a case study based on six years of SCADA data from a PV power plant in Slovenia was conducted within the scope of the OptPV4.0 R&D project. The PV power plant has an installed capacity of about 300 kWp, consists of 19 inverters, 38 strings and about 840 240Wp modules.

For continuous performance monitoring purposes efficient calculations in terms of time and use of computational power are important. Therefore, in a first step we derived a characteristic diagram (Figure 2) from the one-diode model described in section 2.3. Furthermore, a regression model as a function of temperature and irradiance was calculated from the characteristic diagram, which allows processing large amounts of data within a short period of time and allocates dynamic reference values of “P_{MPP}”, “U_{MPP}” and “I_{MPP}”.

The real time application of the calculated reference value “P_{MPP}” to online monitoring is depicted in Figure 4. It had initially been demonstrated that the model replicates the real performance values at a reasonable accuracy. This test showed a mean deviation of about 6 percent between the measured and simulated values. Typically, corrective actions by the operator will only be performed above performance losses of around 10 percent. Therefore, the model is sufficiently accurate to be used for online monitoring and failure detection.

Furthermore, it was detected, that there are high deviations between modelled and measured values near rated module power, which can most likely be explained by gradual module degradation as well as defective irradiation and temperature sensors.

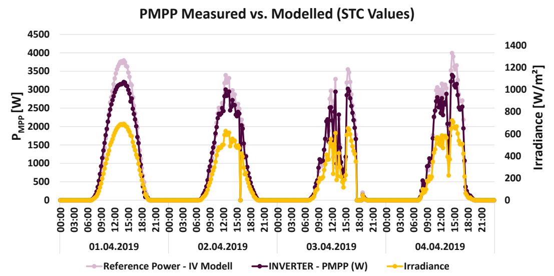

Figure 4: Measured vs. modelled string power

Following that, the use of the so called “energy performance index” (EPI) [16] and dynamic reference values allows to determine the photovoltaic power plant performance and hence possible long-term degradations. The EPI (equation (2)) is defined as the ratio of the measured energy and the expected energy as a function of the actual load condition.

$$EPI = \frac{E_{Measured}}{P_{Model\, f(T,G)} * dt} \qquad (2)$$

The EPI is calculated in regularly assessment periods like days, months, or years. We applied the EPI on all strings of the above described photovoltaic park in a monthly period, as depicted in Figure 5. In addition, a monthly EPI median value of all investigated strings was determined to detect suspicious outliers and gradual degradations in the string performance. The analysis revealed a significant deviation at string “2U04_S1”, as well as a gradual performance decrease of string “1U09_S2”. Furthermore, values greater one were discovered, which indicates an impossible efficiency above the expected nominal value. It is very likely that this effect can be explained by a lack of measured temperature and irradiance data values which led to fewer modelled values for an accurate EPI calculation in certain assessment periods. Consequently, these findings allow detecting sensor problems in PV systems in an easy manner.

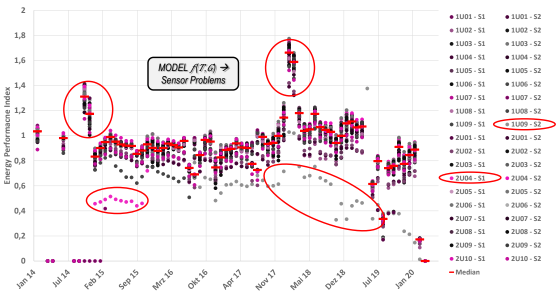

Figure 5: EPI – String comparison

By having detected abnormal behaviour of two strings, the recommendation of corrective action within the integrated concept of model-based monitoring requires the identification of critical components and failure diagnosis.

In order to identify the root cause and critical load situations of critical components, a comprehensive failure potential analysis was performed within the scope of the Austrian OptPV4.0 R&D project. As a result, a failure catalogue covering 50 failure mechanisms in PV systems was established and served as an input for the physical damage models. It turned out, that failure modes like delamination, backsheet cracking, cell cracks, potential induced degradation (PID), burn marks, disconnections of ribbons and defect bypass diodes are mostly reported in photovoltaic modules. This confirms the previous findings in the literature, as stated in 2.2.

To describe the physical damage modelling approach exemplarily, hydrolysis driven failure mechanisms like delamination of PV module junctions will be described in more detail. These damage mechanisms see temperature and humidity as most critical load situations and it has carried out, that this mechanism can be accurately described and calculated by an extended Arrhenius approach with equation (**3**) [11].

$$k_H = A_H * RH^n * e^{\left(-\frac{E_H}{k*T_m}\right)} \qquad (3)$$

k_H describes the damage kinetics, A_H is a curve fitting preexponential factor, R_H the humidity, n a model parameter, E_H is the activation energy for hydrolysis driven reactions, k the Boltzmann's constant and T_M the mean PV module temperature.

We address the modelling process by using a specialized software developed by Uptime-Engineering. This software allows automated periodic calculations of all developed damage models based on SCADA time series data. As a result, the software delivers accumulated damage. In order to rank possible failure modes according to the risk of failure occurrence, the accumulated damage are summarized in an assessment table, as shown in an example in Figure 6. The assessment table allows to compare damage increments of one failure mode (depicted as “Analysis Package”) of all PV system instances. High damage kinetics (highlighted in orange) for a particular failure mode/instance combination indicate a higher failure risk in comparison to other failure modes/instance combination (highlighted in green). In this way, likely root causes for detected performance issues can be identified. This information is a valuable input for field inspection tasks.

Instance / Analysis Package	String 1	String 2	String 3	String 4	String n
Subsystem A					
Analysis Package 1	DPH	DPH	DPH	DPH	...
Analysis Package 2	DPH	DPH	DPH	DPH	...
Subsystem B					
Analysis Package 3	DPH	DPH	DPH	DPH	...
Analysis Package 4	DPH	DPH	DPH	DPH	...

Figure 6: Damage calculation results: PV modules and cabling

The damage calculation for the above as suspicious indicated strings “1U09_S2” and “2U04_S1”, showed that string “1U09_S2” had seen higher thermal aging at electrical contacts, photodegradation and hydrolysis driven aging. As opposite to this, string “2U04_S1” did not show any considerable higher damage sum compared to other strings. It is very likely that this can be explained by quality issues within the PV power system, like cabling or connection errors that needs to be validated by field analysis. This assumption is consistent with the fact that there was no degradation over time detected for string “2U04_S1”

Another analysis of damage calculations on PV inverters showed, that inverter “1U09” had seen high loads at nearly every power electronic device, like IGBTs, capacitors and electrical contacts. Based on the damage sums of string “2U04_S1” no distinct failure mode was detected.

As stated in the introduction, one of the goals of the integrated concept of model-based monitoring was to provide prognosis about future failure events. This can be achieved by a continuous monitoring of the PV system with the presented damage models and by calibration of these models with lifetime data of components. This combination allows to calculate failure rates and hence remaining useful lifetimes for failure prognostics

5 CONCLUSION AND FUTURE OUTLOOK

Our model-based monitoring approach has led us to conclude that by applying modelled dynamic reference values, string “1U09_S2” was detected as defective. In order to diagnose the root cause of the failure, the damage model calculation provided a list of possible candidates which have seen a high failure relevant load and hence a high damage sum. This list includes thermal ageing of PV cabling and connections, photodegradation and/or hydrolysis driven aging of PV modules. In addition, power electronic devices like IGBTs, capacitors and connections in inverter “1U09” have seen high damage sums in thermal aging and/or cycling. Due to the missing correlation of detected abnormal behaviour of string “2U04_S1” and damage accumulations, it can be stated, that with a high probability the system deviation is correlated to quality issues of the string, like cabling or connection errors. This needs to be validated by field analysis.

Finally, an actionable maintenance recommendation and hence a corrective action, can only be generated by limiting the list of possible root cause candidates and performing field analysis of service technicians on possible symptoms correlated to the failure event.

A further important application of the integrated concept of model-based monitoring is the combination with adaptive expert systems. By continuously using the model-based monitoring, getting feedback from service technicians about the degree of accuracy of the diagnosis and adaption of domain knowledge, the precision of automated failure diagnosis will increase. An increased knowledge of the failure statistics of components in combination with linearized damage sums will allow to estimate remaining useful lifetimes for application of predictive maintenance strategies.

Overall, the integrated approach on failure detection and diagnosis contributes to faster response times of corrective actions, less downtime, and an efficient long-term operation at maximum performance of photovoltaic power plants.

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