IP-SOLAR: DEVELOPMENT AND VALIDATION OF A WEB-BASED MONITORING AND DIAGNOSTICS TOOL FOR SOLAR THERMAL SYSTEMS

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Abstract

Large solar thermal systems (LSTS) are a promising market segment for solar energy. However, the realization of LSTS is more challenging compared to smaller plants, in both technical and economical terms. Permanent monitoring, data evaluation and fault detection during the operation of LSTS has shown by Fink et al. (2010) and Peuser et al. (2008) to be crucial for ensuring optimal performance.

The only cost-effective way for permanent surveillance of LSTS operation is to make use of a computer-aided tool that performs as many steps as possible in an automated mode. The ongoing R&D project 'IP-Solar' is developing the scientific basis and the technical fundamentals for such a system, resulting in a prototype of a web-based software tool. This paper presents the current state of development emphasizing the methodology of the operation diagnostics. In particular, the algorithm-based approach, its implementation and testing are described in detail.

1. Introduction

This publication is mainly based on Ohnewein et al. (2010) and expands on software testing results.

1.1. Motivation

While small solar thermal plants have become state of the art in many countries, large solar thermal systems (LSTS) still show huge unused market potential concerning Fink et al. (2008). The decision to build a LSTS generally depends on economic parameters with investors claiming a guarantee for solar energy yields. However, though engineered for a service life of about 25 years, the energy yields of many LSTS have shown by Peuser et al. (2008) to be below expectations: The performance predicted in the engineering phase is not reached, operational faults in the LSTS remain undetected for a long time because the backup system still provides hot water. Besides loss of confidence in the technology, this results in economic losses. Permanently high energy yields are only achieved in monitored installations: ongoing surveillance of plant operation by evaluation of measuring data is required. If conducted by humans, trained expert staff causes high expenses in both time and human resources. For these reasons, IP-Solar aims at an automated process: The web-based software being developed provides users a standardized and low-cost permanent monitoring and failure detection tool.

1.2. Objectives of the R&D Project

IP-Solar ('Intelligent Platform for long-term automated quality assurance and energy output monitoring of solar plants') is the name of both the ongoing R&D project and the LSTS monitoring tool being developed. The aim is to create the scientific basis, the technical fundamentals and a software prototype for the software tool with the features described above. This paper is organized following the main steps of the R&D project: standardization and modularization, development of the methodology for systematic failure analysis, implementation of the methodology in terms of algorithms, verification and validation, software implementation and quality assurance. In this context, the term 'intelligent' refers to combining and automating all these steps.

Two strategies for function control are pursued in IP-Solar: an algorithm-based and a simulation-based approach. The latter is basic research oriented. This paper focuses on the algorithm-based approach.

Table 1. Overview of IP-Solar modules: detail variants, data points, control logics

Module	Module description	# detail variants	# data points	# data points, recommended	# generalized control logics
SOL	solar circuit	12	62	7	15
HST	heat storage	24	24	3	6
AUXH	auxiliary heating	4	34	3	7
DHWP	domestic hot water preparation	32	52	9	11
DNET	distribution net (2-line-systems)	2	27	3	2
SINK	general heat sink	1	3	1	0
DHWIO	domestic hot water input / output	1	0	0	0
CDTA	special connector module	2	0	0	0

2. Standardization and Modularization

In order to design IP-Solar as a market-oriented tool, tailored to the various common configurations and system types of LSTS, extensive market analysis was carried out. 200 existing LSTS in Germany and Austria have been examined. The analysis was based on the hydraulic design, measurement equipment and control strategies of the plants. The state-of-the-art and most widespread system concepts were identified and are pursued in IP-Solar.

We evaluated various modeling approaches, including component-oriented modeling (cf. PolySun) and system-oriented modeling (cf. T*Sol). Finally, a module-oriented modeling approach (cf. Tachion) was considered as best trade-off between standardization, flexibility, complexity and usability. This has led to the concept of a modular design for IP-Solar which specifies hydraulic configurations, measuring equipment and control logics of LSTS (see table 1). The approach is described in detail in Dröscher et al. (2009).

IP-Solar regards not only the solar circuit but the entire energy supply system. For example, all typical DHW configurations for larger solar systems are available as modules; process heat or 2-line-systems are other options. In order to map a plant configuration exactly, the modules can be adapted by means of detail variants. For example, stratified charge of the storage tank in various heights may be chosen as an option. This individual customization allows modeling a wide variety of system types. Finally, the software automatically connects the selected modules and sets them up for the diagnostics.

All modules in table 1 are inside IP-Solar's system boundaries, while decentralized home stations are outside the boundaries. Other sub-systems such as heat pumps, solar cooling or biomass heating systems are currently not included in IP-Solar, but may be added in the future following the same modular approach.

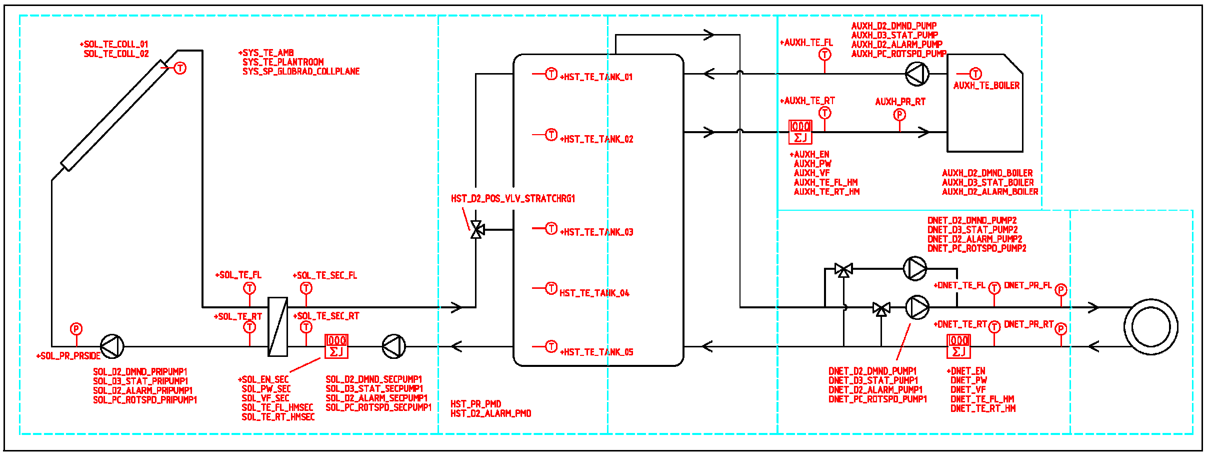


Fig. 1. Modular configuration and data points for one of the pilot plants validated with IP-Solar. Minimum recommended measurement sensors are marked with a '+'.

2.1. Measuring Equipment and Data Acquisition

The modularization process described above also includes the measuring equipment and data acquisition of a solar plant. IP-Solar stipulates no obligatory measuring equipment: rather, it automatically adapts the failure diagnostics to the existing measuring concept, taking into account a wide variety of user-installed sensors. These include temperature, pressure, irradiance and volume flow sensors as well as heat meters and various control signals such as on/off signals, rotation speeds etc. Beyond defining standardized data points (see fig. 1 for an example), IP-Solar recommends a 'minimum measuring equipment' including those sensors that are essential to detect the most important failures.

IP-Solar can understand virtually any data format provided by control systems and converts it to a standardized internal IP-Solar data format. The only requirement to the control system is the capability to send or let IP-Solar retrieve the ongoing measuring data via an Ethernet connection. Thus, IP-Solar can work with virtually any important control system. Independent of controller manufacturer, the sensors of a solar plant are mapped onto the standardized IP-Solar data points. Each sensor is assigned a specific position and a sensor type with determined properties (see chapter 3.4. for details).

Besides the data transfer, neither the control nor the measuring equipment of a solar plant needs to be adapted in order to make IP-Solar work. Basically, no extra peripheral hard- or software is necessary. Measuring data may be imported into the IP-Solar database in quasi real-time applying data filtering methods such as a compliance test with regular expressions, check of various error limits and an optional unit conversion (e.g. from °F to °C). IP-Solar comprises storage of data in a central database for an unlimited period; this means comprehensive documentation for all monitored installations.

3. Methodology of Failure Analysis

3.1. State of the Art

During extensive literature research, a series of function and yield control methods for solar thermal plants have been identified. Beside methods for manual monitoring of operation and energy yields such as the Optisol approach explained in Fink et al. (2006), all known methods for automated fault detection have been examined. Here is a selection of the most remarkable approaches. Altgeld (1999) was the first to use industrial techniques for failure analysis (namely FMEA and fault-tree analysis). However, the number of detectable failures is limited and the method is restricted so small installations (less than 5m²).

Räber (1997) presented a spectral method, based on Fourier transformation of a temperature step response signal and a subsequent pattern comparison that allows the identification of a few failures. This method, limited to the solar circuit, was tested by Grossenbacher (2003).

Deviations between simulation results and measuring data of a solar plant are another option, but in general failure localization is difficult. The Input-Output method by Pärisch and Vanoli (2007), though limited to the solar and to some extent to the heat storage circuit, was commercially implemented. Related approaches include the ISTT method explained by Staudacher et al. (2004), designed to verify promised energy yields, and the TRNSYS based Kassel method shown in de Keizer et al. (2010) and Wiese et al. (2005). The latter is currently limited to basic research.

Several approaches such as Parabel Energiesysteme GmbH (2010) are not manufacturer-independent or are limited to the solar circuit. Gebauer's (2007) Solar Expert method is based on an innovative diagnostic expert system and is available online, but automation seems to be difficult following this approach.

3.2. Failure Analysis, FMECA

The IP-Solar diagnostic system is based on a thorough failure analysis of solar installations which includes all system parts (modules) mentioned above. First of all, two important terms were clarified: malfunction and failure. A malfunction indicates the state of a system component not operating as expected (example: broken collector cover). It is generally not possible to detect a malfunction directly by means of measuring data; following the example, there is generally no glass breakage sensor on a solar collector. On the contrary, a failure is the effect of a malfunction on the system; it is the way in which a malfunction becomes visible and quantifiable by evaluating measuring data; going back to the example, the power output of a collector with broken cover will be lower than expected.

The project consortium collected its experience in LSTS design and operation in a systematic expert system. As an established method, an FMECA (failure mode, effect and criticality analysis) was performed on a component basis: for each component of a solar installation, all possible malfunctions were specified. The next step was to gather all possible failures resulting from the malfunctions. In doing so, the failures were expressed as detailed questions about the system behavior, for example: "Is the volume flow in the secondary circuit currently too low?", or "Has the power of the heat exchanger decreased over the last months?". A total of 199 malfunctions and 193 failures were identified.

Table 2. Criteria for evaluating the system failures identified in the FMECA

failure classification groups	general failures	critical safety failures
	failures due to broken measuring sensors	failures due to inadequate system control
	alarm signals from the control	
criticality analysis effects	safety-critical	reduced comfort
	possible system damage	minor reduced comfort
	reduced solar energy yield	suboptimal operation of a component
failure evaluation criteria	severity of all malfunctions linked to the failure	severity of the failure on the system
	frequency of occurrence (based on experience)	complexity of detection
	time scale on which the failure occurs	

The failures were classified into groups and a criticality analysis was performed by assessing their effects considering the evaluation criteria stated in table 2. Based on these criteria, a priority figure was calculated for each failure, serving as a basis for the development of the diagnostic algorithms.

3.3. Key Figures

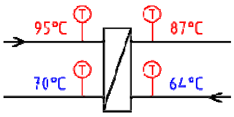
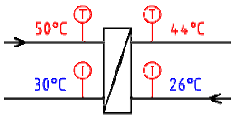
The calculation of key figures from measuring data was identified as a simple possibility for a characterization and a quick check of a system's behavior. Typical key figures include solar energy yield, average return temperatures, solar system efficiency or number of heat storage charging cycles. In total, 92 key figures are calculated automatically on a daily, monthly and yearly basis.

3.4. Error Propagation

The uncertainty of a calculated value is affected by the uncertainties of the underlying sensor values. Neglecting the uncertainty treatment thus carries the risk of (a) generating false alarms or (b) not detecting an existent failure. Hence, some error propagation technique must be included so as to allow accurate and powerful failure detection.

IP-Solar incorporates automatic error propagation techniques following GUM "Type B" from ISO/IEC Guide 98-3 (2008). As generally only maximum measuring errors are available from sensor specifications, rectangular probability distributions are assumed. All function derivatives are calculated by means of central differencing. The maximum measuring errors are taken from predefined sensor types (e.g. "Pt1000 DIN class B") which are selected when a new plant is added to IP-Solar. Thus, the "true" uncertainties of the installed measuring equipment are considered. Consequently, better measuring equipment leads to more accurate statements and improved failure detection performance.

Table 3. Statements remain fuzzy if measuring uncertainties are neglected: worst vs. best case example

	worst case	**best case**
setting		
sensor equipment	Pt1000 DIN class B, 2-wire system assumed connection error: 0.9 K	Pt1000 DIN class 1/3B, 4-wire system assumed connection error: 0.2 K
ΔT_{log}	6.95 K	4.93 K
uncertainty of ΔT_{log}	1.53 K	0.35 K
relative error	21.9%	7.1%
possible ΔT_{log} range, 95% confidence	5.43…8.48K can be good or bad, low significance	4.58…5.28K sharp statement, high significance

4. Algorithms for Failure Diagnostics

IP-Solar performs a detailed system monitoring and failure detection analysis based on different classes of diagnostic algorithms. These five classes of algorithms are described hereafter.

Class 1, failure algorithms try to find answers to the specific failure questions stated in the FMECA. A failure algorithm answers the failure question by returning a specific value: 0 if the failure is not present in the tested time interval, 1 if it is present and reaches the warning limit, 2 if it exceeds a critical limit. Warning and critical limits are defined specifically for each algorithm and may be adapted to each solar plant. The selection of algorithms to be executed and the way the algorithms work internally depend on the hydraulic configuration and on the sensors installed at the plant. Failure algorithms can be enabled or disabled by the user for a specific plant. All enabled algorithms are run automatically as soon as new measuring data are available. Failure algorithms vary in complexity, ranging from simple exceeded limit checks to self-learning regression-based algorithms.

Class 2, key figure algorithms are used to calculate the key figures described in chapter 3.3.

Class 3, data base functions: Failure and key figure algorithms retrieve measuring data and a variety of parameters from the central IP-Solar database by taking advantage of standardized data base functions that can be used to get data a set or min / max / average values of the data set. The data base functions perform several data format checks, they verify data information density (too many missing or NaN values) and they map different data sets to a common time grid, making future calculations easier. In total, there are 7 data base functions.

Class 4, auxiliary algorithms may be called by any other algorithm. An example is the function "hasMinOPTimeExpired" that checks whether a pump is currently operating and has been operating for at least its set **minimum** operating time. This same function may be used for any pump in the system. In total, there are approximately 45 auxiliary algorithms.

Class 5, criticality Algorithms: Should a failure detection algorithm return a "warning" or "critical" result, a criticality algorithm is called: its task is to statistically assess a series of return values and take into account other parameters such as the severity of the failure in question, in order to calculate a criticality value (0%...100%) that represents the degree of harm that the failure pattern is causing in the system.

Class 6, notification Algorithms: In case unwanted system behavior is detected, IP-Solar provides the user with a specific notification by SMS or email. The constantly updated criticality values are used to combine the capabilities of sending the messages quickly and of preventing false alarms.

5. Verification and Validation

All of the described algorithms and functions have been tested independently, which means that the algorithm author is different from the algorithm tester. The verification and validation process is highly standardized and automated: It comprises generating test data, setting up expected results files, running automated testing procedures and comparing the outcomes between actual and expected results.

For validation purposes, IP-Solar is being tested on 3 pilot plants (commercial installations) located in Graz, Austria. As the plants have different hydraulic configurations, the functionality for a variety of systems is being examined. The 3 pilot installations are of types 'hot water generation', '2-line-system' and 'district heating supply'. Their measuring data are being recorded since mid 2009, delivering new data to IP-Solar every few minutes. The algorithms described above run automatically on these data.

5.1. Test procedures and test results

Currently approximately 75% of all developed algorithms have been tested and work as required.

Unit testing is a procedure in which individual algorithms are validated with **artificial data** to check their expected behavior. For this purpose smallest possible pieces of testable algorithms have been isolated and tested neglecting all other algorithms of the application. In a first step database functions and auxiliary functions have been checked due to their functionality. After a valid result in the first step, failure and key figure algorithms have been tested in a second step. An example unit test result for a failure algorithm is shown in fig. 2.

Historical data testing uses real data from the three pilot plants mentioned before. The testing applies different groups of algorithms (class 1 and class 2) in individual tests on the same historical data. For instance the solar yield may be calculated for a certain time period. Additionally the critical collector temperature is checked in the same period. In the first step algorithms calculate results, which are verified by the algorithm tester. In a second step, input data values and expected results are modified to exceed limits. By reaching warning and critical limits, failure algorithms are activated and expected failure-messages are generated.

From the software developing point of view, successful unit tests declare well working parts. Historical data tests make a point to the operative users: Linking historical data testing to criticality algorithms (class 5), which calculate the degree of harm that the failure pattern is causing in the system.

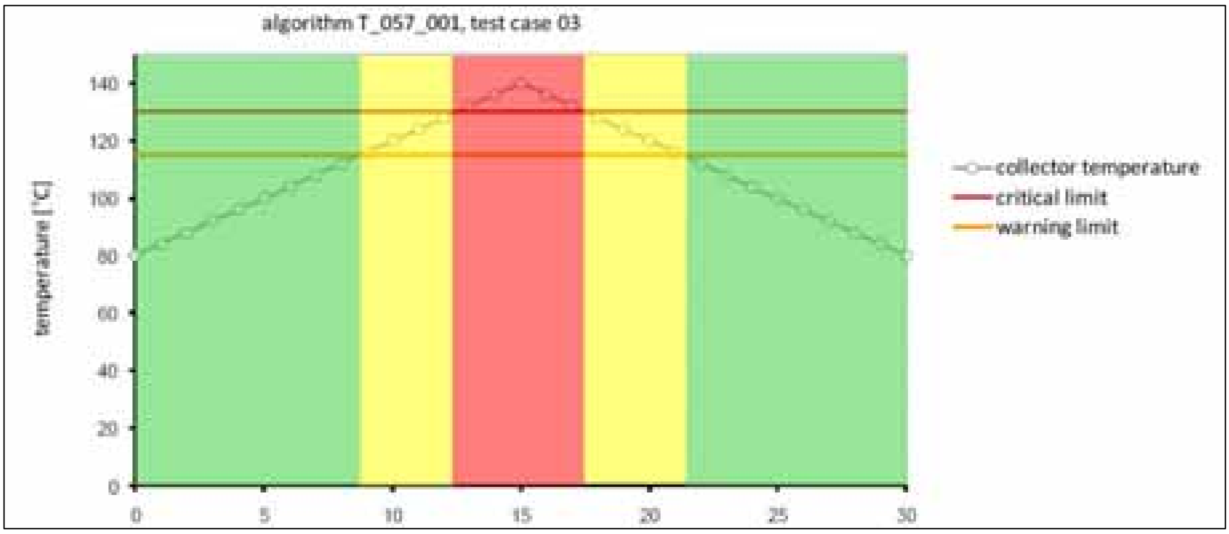


Fig. 2. Example of a unit test result

6. Software Issues

IP-Solar comes with no distributed software, it is available at any internet-connected PC; the web-based design makes it straightforward to use and maintenance-free for users. All diagnostics are run on a centralized server which also collects the measuring data of the monitored plants in the central database and runs the IP-Solar internet platform. On this platform, among other things users can prepare data charts, export measuring data and evaluation results and see a history of the diagnostics' results.

7. Quality Assurance

Quality assurance measures adopted in the IP-Solar R&D project include clear competences and responsibilities for each task, thorough documentation and traceability (glossary, user requirement documents, use cases, pseudo code definition, online document management tool etc.). General principles of risk avoidance such as dual control prior release form the basic foundation of internal control. As to the algorithms, a stringent verification and validation procedure guarantees a high quality level.

8. Conclusions

This paper describes the R&D basis and validation for a monitoring and diagnostics tool for large solar thermal installations (LSTS). Only continuous quality assurance guarantees satisfactory economic performance and maximum primary energy savings. This is where IP-Solar contributes by increasing technical and financial reliability of LSTS: IP-Solar is also a tool for reducing operational risk, leading to optimized and reliable economics and reduced fossil fuel consumption and CO_2 emissions. In the long term, this quality increase will contribute to spreading the technology.

The development of IP-Solar is especially interesting in view of the current development of standards about function and yield control of LSTS, described in QAiST (2010) and in VDI 2169 (2007). Target user groups of IP-Solar are the end-users of a solar installation and its operators, but also scientific institutions and public institutions like funding authorities who may use it as a tool supporting the targeted use of subsidies based on real energy yields, and offering a concise survey of existing LSTS. An exciting aspect is the fact that the basic methodology of IP-Solar is easily extendable to smaller plants and to other scopes of application where automatic monitoring and failure detection are important.

Here are the key features of the IP-Solar monitoring and failure detection tool: IP-Solar…

- provides permanent plant surveillance

- is independent of manufacturer and plant design
- sends users a targeted notification in the case a failure occurs
- results are available at any internet-connected PC, no extra software needed
- develops a highly sophisticated diagnostics kernel for analyzing solar plant behavior
- is market-oriented: its modular approach is suitable for numerous common system types of LSTS
- analyzes the entire system (solar loop, but also auxiliary heating, hot water generation,…)
- goes for high automation level and will therefore need little human interaction
- adapts to existing measuring and data-logging equipment
- works with any solar plant location worldwide

Currently, the functionality of the IP-Solar prototype is limited. The next steps in the R&D project are to verify and validate live diagnostic algorithms and corresponding notification events and to enhance the user interface for improving the efficiency of testing tasks.

For more information about IP-Solar visit www.ip-solar.com.

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