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Fault Detection and Fault Diagnosis for Large Scale Solar Thermal Systems

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Abstract: A four-step concept for fault detection and fault diagnosis for solar thermal systems has been developed in the framework of the ongoing research activities at Kassel University. This concept is able to combine different general approaches for fault detection and fault diagnosis in one structure. Additionally it introduces a systematic categorization of information and a more precise terminology by distinguishing between element sensor values, measured values, features and symptoms.

Otkrivanje i dijagnoza kvarova u velikim solarnim toplinskim sustavima

Izvorni znanstveni rad

Sažetak: Koncept u četiri koraka za otkrivanje i dijagnozu kvarova (FDD) u velikim solarnim toplinskim sustavima je razvijen u okviru tekućih istraživačkih aktivnosti na Sveučilištu Kassel. Ovaj koncept kombinira različite opće pristupe za otkrivanje i dijagnozu kvarova u jednoj strukturi. Osim toga, uvodi se sustavna kategorizacija podataka i preciznija terminologija prema razlikovanju između veličina dobivenih iz osjetnika, mjerenih veličina, svojstava i simptoma za pojedine elemente sustava.

Keywords

Solar Thermal Systems
Fault Detection
Fault Diagnosis
Internet based Monitoring
Automatic Function Control

Ključne riječi

Solarni toplinski sustavi
Otkrivanje kvarova
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Automatska kontrola funkcija

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1. Introduction

Faults may occur throughout the lifetime of solar thermal systems. The reasons are manifold; for example, poor system design, breakdown of components or external influences can cause faults. Many faults are not obvious to the user and therefore remain undetected for a long period, causing losses and risk of further damage. Automatic fault detection helps to detect system failures at an early stage. In addition to fault detection, it is often useful to include fault diagnosis to identify the fault. Thereby, the time for on-site investigations and repair costs can be reduced.

In the framework of the ongoing research activities at Kassel University, a four-step concept for fault detection and fault diagnosis for solar thermal systems has been developed. This concept is able to combine different general approaches for fault detection and fault diagnosis in one structure using algorithms and system simulations. Furthermore, it introduces a systematic categorization of information and a more precise terminology by distinguishing between element sensor values, measured values, features and symptoms. In this contribution, the technical configuration installed at Kassel University is briefly described. Subsequently, the four-step concept is described in detail and includes several examples.

2. Technical Configuration installed at Kassel University

The investigations in automatic fault detection and fault diagnosis are based on measured data. These data are measured by sensors and are cached locally in a data logger (Figure 1). A communication unit transmits the data to a central server at regular intervals. The incoming data are automatically parsed and stored into a database on the server [1]. There, the data can be analyzed manually with a visualization module or they can be analyzed automatically by the Fault Detection and Diagnosis (FDD) methods using algorithms. The development of automated FDD methods is the focus of the research activities.

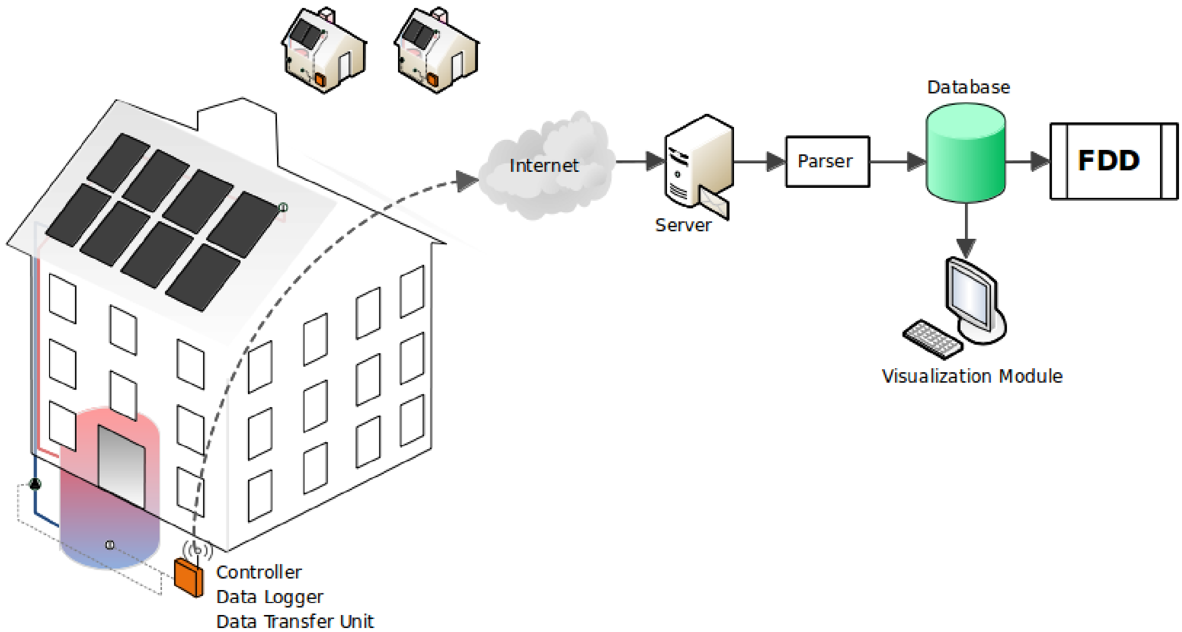

Figure 1. Technical configuration of data acquisition for the internet based fault detection and fault diagnosis (FDD).
Slika 1. Konfiguracija akvizicije podataka za otkrivanje i dijagnozu kvarova (FDD) pomoću interneta.

3. Four-Step Concept for FDD

Different methods exist to detect and identify faults [2-4]. The approaches behind these methods vary widely. While some of them perform basic checks of the measured values and deliver only little information about the observed process, others, like those including system simulations, are more sophisticated and able to deliver more detailed information. Most of these methods can be combined and implemented as algorithms [5]. Therefore an algorithm-based approach for FDD seems to be promising. This approach is being investigated at Kassel University.

3.1. State-of-the-art fault detection methods

Different procedures for automated function control of solar thermal systems were developed in the past [6]. They can be divided into two general categories: The ones requiring a system specific training phase – some even with artificially produced faults – and those procedures using existing knowledge on fault appearance. Fault detection based on neural networks and the Spectral Method (see [6]) can be assigned to the first category. However, the majority of the existing procedures are based on previously known fault appearances, such as FUKS, IOC, GRS, ISST, KU (see [6]) and IP-Solar [7].

As there is a huge variety in the system design of large scale solar thermal applications, the procedures of the first category would require a system-specific training phase. Furthermore, thanks to different projects like Solarthermie2000, [8] and [9], a broad knowledge base is available, which can be used. For these two reasons the second category of the procedures appears to be more promising.

3.2. Four-Step Concept

All of the principal methods of fault detection and fault diagnosis have their specific advantages and disadvantages, so that none of them can be generally considered as superior [4]. Many of these general methods of fault detection and fault diagnosis can be used for long-term monitoring of solar thermal systems.

Based on [2-4], an algorithm based concept for automatic FDD has been developed at Kassel University that makes it possible to combine the advantages of these different methods. At its core, this concept is based on a four-step process, structuring relevant information on the one hand and performing the automatic data processing on the other hand. In Figure 2 the four-step concept is shown.

In terms of accuracy of fault recognition, two different levels can be distinguished: fault detection and fault diagnosis. While fault detection only notices whether a fault has occurred in the system, the fault can be further identified by fault diagnosis. In this concept, fault detection and diagnosis are performed in four consecutive steps.

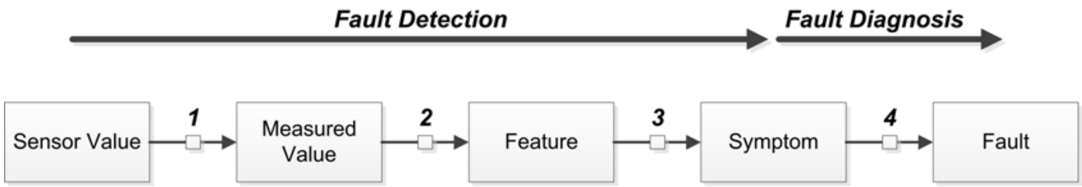

Figure 2. Four-step concept of the algorithm-based FDD.
Slika 2. Koncept algoritma u četiri koraka za FDD.

Step 1: Sensor Value → Measured Value:

In the first step, measured values are calculated by algorithms from the raw output signals of the sensors. This can be done by applying a simple transfer function, by more complex methods like signal processing or by using process models. In the latter case it is even possible to calculate measured values for positions where actually no sensors are installed or where the sensors are out of order.

Step 2: Measured Value → Feature

As a second step, features are generated by algorithms or by external simulations using the measured values calculated in the previous step 1 and through additional information. Features are values which may correlate with faults in a defined manner. They might exceed defined limits or appear in an implausible combination in the case of a system failure. Typical features are temperatures, temperature differences, key figures or variables describing a state like "Pump in primary solar loop is on!" or "It is night!"

Since the feature generation plays a key role, it is described in more detail. In the following concept, three categories of feature generation can be distinguished:

1. feature generation by direct use of measured values,
2. feature generation by using signal processing,
3. feature generation by using process models.

Feature generation by direct use of measurement values

In the most basic case the measured value itself is the feature and is checked in terms of certain defined limits. By combining different measured values, more sophisticated features can be generated. Some examples are individual temperatures, temperature differences or other key figures.

Feature generation by using signal processing

Some faults are reflected in the temporal, spectral or stochastic behavior of the measurement signals [10]. To extract this information, it is required to use signal processing methods like Fourier transformation or statistical analysis. Then, features like the amplitude spectrum or empirical variance can be calculated and analyzed.

Feature generation by using process models

In case of feature generation by using process models, a mathematical or causal model is required that represents the fault free operation of the system. It is possible to generate different features by utilizing the process model together with measured data. Here, different approaches exist [2, 3].

One basic option is to use a mathematical process model to calculate expected values for process variables and to compare them with the actually measured process variables. The process model can be implemented within algorithms or in external simulation software like TRNSYS. More complex methods based on process models can be used to estimate parameters or state variables.

In the present concept, causal process models also play a key role. They describe the process in a knowledge based approach, often by using if-then rules similar to human knowledge. This opens up the possibility of integrating expert knowledge into feature generation. A simple example of a causal process model is the following:

Feature 1: Correlation between state of the pump in the primary solar loop and the respective volume flow = {0, true, false}

If:

Pump in solar circuit is on

Then:

There should be a volume flow in the solar circuit.

Step 3: Feature → Symptom

In the third step, the generated features are used to determine whether a fault occurs. Therefore the features are observed. The generated features are observed with regard to certain limits or with regard to implausible constellations. The appearance of a symptom is a sufficient criterion for one or more faults in the system.

For example the symptom "The measured energy yield of the solar circuit is below the expected one!" can be detected through a limit checking of the feature "Measured energy yield of the solar circuit". The symptom "Control signal of solar circuit pump is on, but no volume flow detected!" can be realized by plausibility checks of the respective features.

Step 4: Symptom → Fault

The existence of at least one fault in the system is proven by the appearance of a symptom. The exact fault often remains unspecified since symptoms can appear due to different faults. A further step is required to identify the system fault more in detail. This enables the system operator to evaluate the urgency of intervention and reduces the time for fault analysis on site. So in the fourth step fault diagnosis is performed.

Many different methods of fault diagnosis have been developed in the past. Technically they can generally be divided into classification methods and inference methods [2]. Classification methods typically do not require any detailed system description since they focus on pattern recognition. By contrast, inference methods require structural system description to determine the fault. Structural system information is, for example, system reaction in case of faults like "In case of a broken pump no volume flow is available".

In the present concept, the "certain classification by decision tables" [4] out of the classification methods is used. The integration of more sophisticated approaches is planned. In the following sections, the previous theoretical formulations will be concretized by an example.

4. Explanation of the four-step concept with an example

Currently, various large scale solar thermal systems are monitored by Kassel University. A fault occurred at one of the systems on the 5th of June 2011, about 13:30 PM: at a tilted global irradiance of more than 1000 W/m^2, the flow temperature in the primary solar loop increases to more than 100°C (Figure 3). At this temperature, the control turns off the pump to protect the components in the solar loop. As in previous days, the system goes into stagnation. The first and second stagnation phases proceed as expected. In the third stagnation phase the maximum pressure of the primary solar loop is exceeded (Figure 4). Therefore, the safety valve opens and solar fluid is released, resulting in a reduced pressure. During the next days, significant pressure variations occur in the primary solar loop when the irradiance is high. Four days later, on the 9th of June, the primary solar loop is refilled and the system operates as usual.

In Figure 5, the described fault is presented as a causal order of events. The individual events are classified into one of the following categories of the four-step method, feature, symptom or fault. Features are framed by a continuous line, symptoms by a dashed line and faults by a dash-dotted line. Events that can automatically be detected with established sensors are indicated by a check mark, events that cannot easily be detected are indicated by a cross.

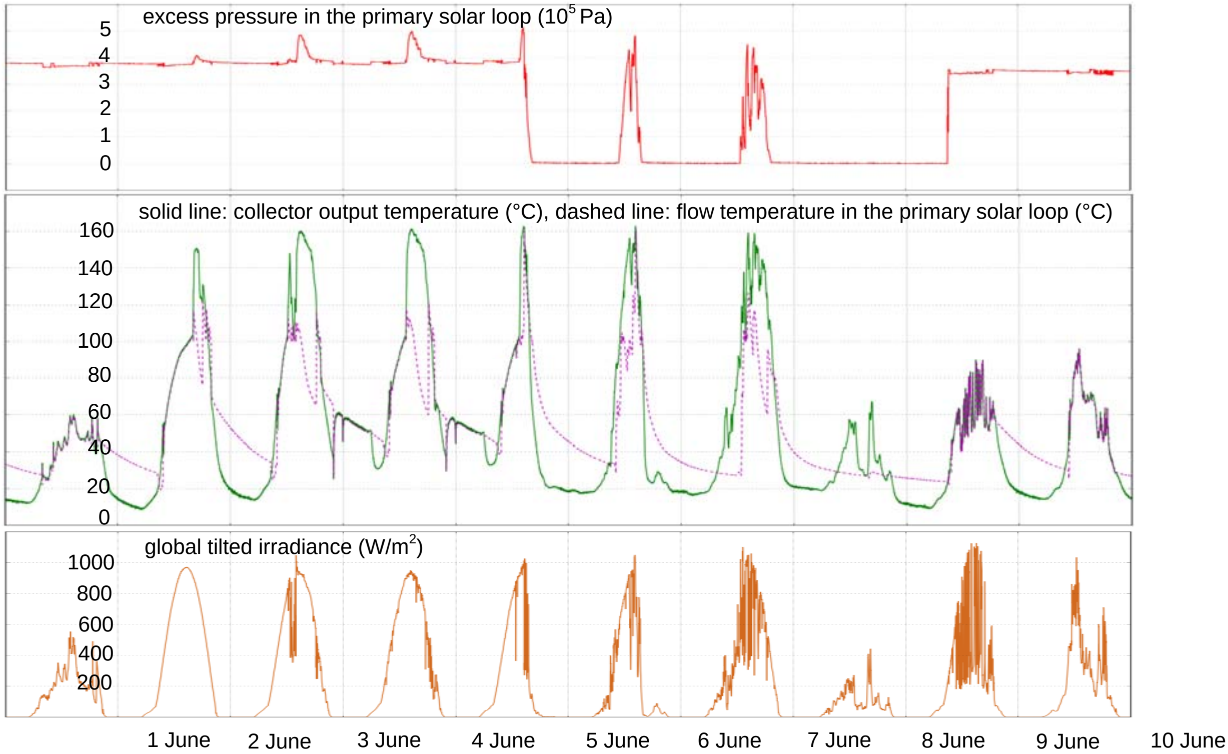

Figure 3. Excess pressure in the primary solar loop, the collector output temperature and the flow temperature in the primary solar loop and the global tilted irradiance between the 1st and the 10th of June 2011. The time resolution of the measured data is one minute. In this time interval the solar storage is not completely loaded.

Slika 3. Višak tlaka u primarnom solarnom krugu, izlazna temperatura i temperatura toka u primarnom solarnom krugu, I globalna dozračena energija na nagnutu plohu između 1. i 10. Lipnja 2011. godine. Vremenski korak između mjerenja je jedna minuta. U ovom vremenskom intervalu solarni spremnik nije potpuno napunjen.

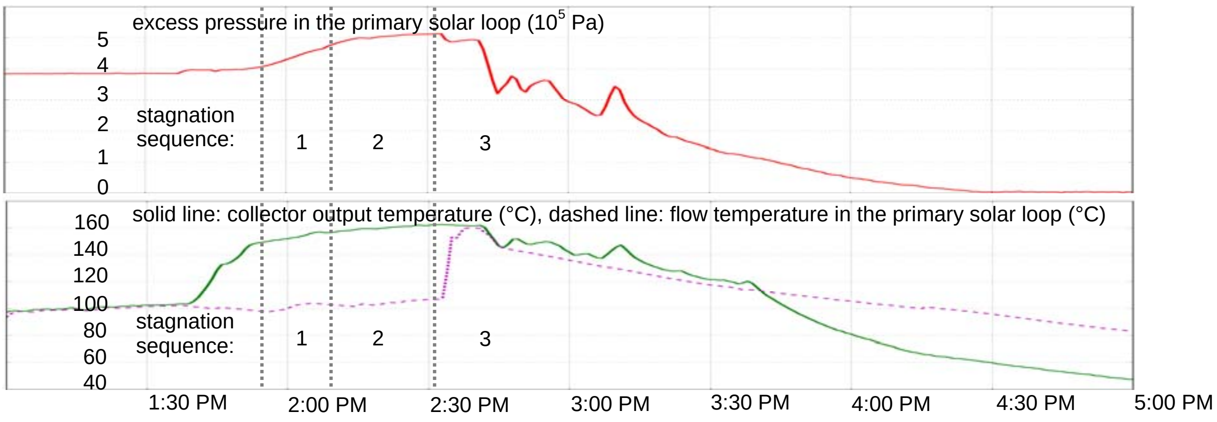

Figure 4. Excess pressure in the solar primary circuit, the collector output temperature and the flow temperature in the primary solar loop, 5th of June 2011 1:00 PM to 5:00 PM.

Slika 4. Višak tlaka u primarnom solarnom krugu, izazna temperature iz kolektora (dijagam dolje, puna linija) i temperatura polaza (dijagram dolje, crtkana linija), 5. lipnja 2011. od 13:00 h do 17:00 h.

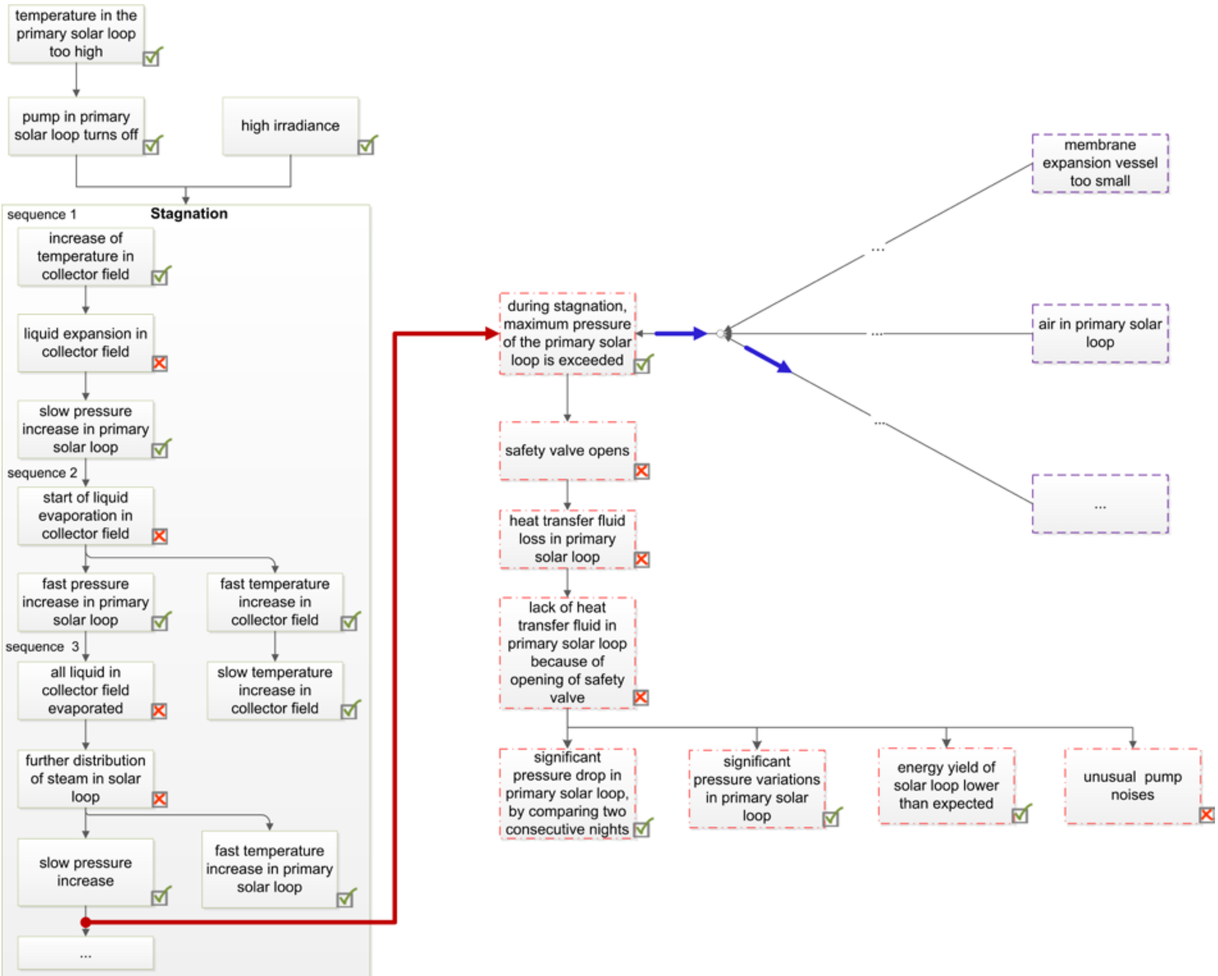

Figure 5. Fault situation as causal link between different events that are categorised into features, symptoms and faults according to the four step concept. Features are framed by a continuous line, symptoms by a dashed line and faults by a dash-dotted line. Events that can automatically be detected with established sensors are indicated by a check mark, others by a cross.

Slika 5. Slučaj sa kvarom u sustavu, kao uzročna veza između različitih događaja koji su karakterizirani prema svojstvima, simptomima i kvarovima prema konceptu od četiri koraka. Svojstva su uokvirena punom linijom, simptomi sa isprekidanom linijom i kvarovi sa crta-točka linijom. Događaji koji mogu biti automatski detektirani senzorima su označeni kvačicom, a drugi križićem.

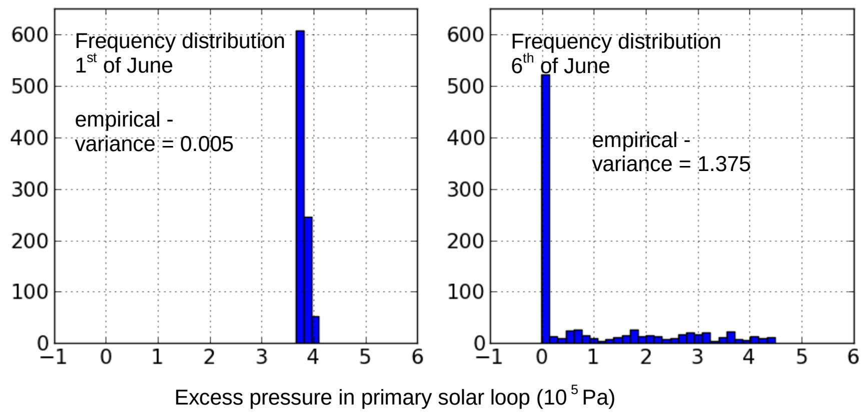

Figure 6. Frequency distribution and the empirical variance of the excess pressure in primary solar loop. Left: (1st of June) represents the expected typical frequency distribution of the fault free process. Right: (6th of June) represents a day with a high pressure variation in the solar loop.

Slika 6. Frekvencija distribucije I empirijska varijanca viška tlaka u primarnom solarnom krugu.

On the 5th of June, initially only those features occur which lead to a stagnating solar thermal system. In the third stagnation phase a fault can be noticed, since the maximum pressure in the solar primary loop is exceeded. The symptom "During stagnation the maximum pressure in the solar primary loop is exceeded" appears. This symptom leads to a number of other symptoms. In Figure 5, different potential faults are shown that could have caused these symptoms. The fault diagnosis process is indicated by two short arrows.

The three categories of generating features are illustrated hereafter, by using the following events: "Flow temperature of solar loop too high", "High variations of the pressure in primary solar loop" and "Energy yield of solar circuit lower than expected"

Feature generation by direct use of measurement values

The feature "Flow temperature of solar loop too high" can be generated by direct use of the measurement temperatures. Therefore the following simple algorithm is applied:

If:

Flow temperature of solar loop > 100°C

Then:

Flow temperature of solar loop too high = True

Feature generation by using signal processing

In the following case the symptom "High variations of the pressure in solar loop" is detected by signal processing. Therefore the frequency distribution of the excess pressure of the solar loop is analyzed for each day. In Figure 6 the frequency distribution of two days is shown. The figure for the 1st of June represents the expected typical frequency distribution of the fault-free process, whereas the figure for the 6th of June represents a day with a high variation of pressure in the solar loop due to the lack of heat transfer fluid. As one can see, they differ from each other. One suitable option to describe this difference is the empirical variance, which is also shown in Figure 6. The figure shows that these values differ considerably for these boundary conditions, so they can be used within an automated fault detection process.

Feature generation by using process models

The symptom "Energy yield of solar circuit lower than expected" requires two features: "Expected energy yield of solar circuit" and the "Measured energy yield of solar circuit". The feature "Expected energy yield of solar circuit" is calculated by a process model that represents the fault free operation of the system. This can be performed by an algorithm or by using simulation software like TRNSYS. Additionally, the feature "Measured energy yield of solar circuit" is calculated by using different measured values. Subsequently these features are compared and in case of a deviation beyond certain limits, the symptom "Energy yield of solar circuit lower than expected" appears. Hereby the occurrence of one or more faults in the system is proven.

5. Conclusion

In the framework of the ongoing research activities at Kassel University, a four-step concept for fault detection and fault diagnosis for solar thermal systems has been developed. This concept makes it possible to bring together different approaches for fault detection and fault diagnosis within one structure. Additionally, it introduces a systematic categorization of relevant information and a more precise terminology to describe the fault detection process by distinguishing between element sensor values, measured values, features and symptoms.

This concept has been tested by algorithms, within an expert system and by fault descriptions extracted by literature research. In all cases its effectiveness could be proven.

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