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"Development of a Model-Based Diagnosis Algorithm oriented towards Solid Oxide Fuel Cell Systems: Approach and Application"

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ABSTRACT

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Abstract

The present dissertation illustrates the complete procedure of developing a model-based diagnosis algorithm and shows its application to a pre-commercial Solid Oxide Fuel Cell (SOFC) system. The main motivations of this work can be found in the increasing demand for diagnostic techniques aimed at both ensuring system optimal performance and required lifetime. The purpose of a diagnostic algorithm is to detect and isolate undesired states (i.e. faults) within the system under study (e.g. both the stack and balance of plant – BOP – components of an SOFC system). The understanding of the main mechanisms inducing malfunctions or, in the worst case, abrupt interruptions (i.e. failures) of the system allows the definition of suitable control strategies to avoid these events and to ensure the required system performance.

Among all the diagnostic techniques available in literature, a model-based fault diagnosis methodology is taken into account. According to this technique, a process model is exploited to treat the data measured during the system operation to obtain insightful indicators of the system state. More in details, the measured data are compared to simulated variables to extract features, i.e. mathematical residuals, which are representative of the monitored variables behavior. The residuals computation is performed during the *monitoring process*. The detection of undesired or unexpected system behaviors is carried out through the comparison of the collected residuals to reference threshold values. These values are suitably tuned to take into account several uncertainties, like model inaccuracy and measurement noise, and the necessity to detect incipient faults. The comparison of the computed residuals to these thresholds allows the generation of analytical symptoms, which indicate whether an undesired event is occurring or not. The arise of a symptom points out that the behavior of the related variable is abnormal, completing the *detection process*. At this stage, although the occurrence of a fault is observed, its type is still unknown. To accomplish this last task, a reference set of information is exploited for the identification of the malfunction nature and for the isolation of the faulty component(s) (*isolation process*). These information comprise the main faults the system can be affected by and the variables conditioned by the occurrence of these faults. The symptoms collected during the detection phase, which are representative of the variables showing an irregular (or unexpected) behavior, are compared to the reference information to correctly locate the fault on the system.

The first part of this manuscript entails the design procedure of a generic model-based diagnosis algorithm, describing in detail the development of the mathematical model and the definition of the reference information required by the methodology. The presented model derives from an SOFC system model, developed by Sorrentino et al. [1][2]. This model is based on a lumped approach and is able to simulate both steady and dynamic behaviors of the system state variables. The stack is assumed planar and co-flow and its voltage behavior is represented by a non-linear regression, function of fuel utilization, current density, excess of air and the temperatures at the stack inlet and at the stack outlet. On one hand, the temperature regulation of the stack inlet flows is achieved by means of two by-pass valves, one at the anode side and one at the cathode side. On the other hand, the stack inner temperature control is fulfilled through a PI controller, which acts on the air blower power to regulate the inlet air flow. The novelty of the presented model consists in several sub-models specifically developed to simulate the considered system both in normal and in faulty conditions. This feature allows the utilization of the model for the offline definition of the reference information exploited for the isolation process.

The reference information help in the isolation of the undesired event(s) occurring in the system during its normal operation. This task can be achieved through the correct identification of the relationships among the symptoms, generated during the detection process, and the possible faults the system can cope with. In the present work, a Fault Signature Matrix (FSM) developed by Arsie et al. [3] following a Fault Tree Analysis (FTA), is considered as the basis for the development of the aforementioned reference information. This FSM is improved through the simulation of different kind of faults in order to understand both the direct and the indirect correlations among the

faults and the system variables. Moreover, the real effects induced by the considered fault on the affected variables are defined in terms of quantitative drifts of the variables values from the normal condition. To achieve this task, the fault sub-models previously introduced are exploited to simulate the effects of several faults.

For the purpose of this work, five different faults related to an SOFC system are simulated, that are i) an increase in the air blower mechanical losses, ii) an air leakage, iii) a temperature controller failure, iv) a pre-reformer heat exchange surface corrosion and v) an increase in cell ohmic resistance. Through the faults simulation, a set of residuals is collected and its comparison with different threshold levels highlights the quantitative relationships among the faults and the conditioned variables. In this way, it is possible to point out the difference between an FSM developed through a heuristic approach (i.e. the FTA), accounting only for the qualitative relationships among the faults and the symptoms, and the one developed considering also the system sensitivity to the faults magnitude.

The second part of this thesis entails the characterization and the validation of the developed diagnostic algorithm on a pre-commercial micro-Combined Heat and Power (μ-CHP) SOFC system, the Galileo 1000N, manufactured by the Swiss company HEXIS AG. A dedicated experimental activity has been performed in order to induce controlled faulty states in the system. The further original feature of this work consists in the design of well-defined procedures to mimic faults on a real SOFC system. In some cases, the procedure involves only suitable maneuvers via software control system, whereas in other cases, specific hardware modifications are required.

Before applying the developed diagnostic algorithm to the Galileo 1000N, an adaptation process is performed, in order to suit each part of the algorithm to the system under analysis. The need for a fast and handy model, which can be rapidly tuned by the algorithm user, led to the development of a maps-based model to simulate the system in normal conditions and to extract residuals. This model exploits the average values of the monitored variables through numerical maps, which are function of the operating condition set-point values. Additionally, the FSM improved off-line via faults simulation is further modified taking into account the number of variables practically monitorable and the system control strategies. Moreover, a statistical hypothesis test is implemented in order to evaluate the probability of false alarm and missed fault. These analysis is significant for the correct interpretation of the generated symptoms during the detection phase.

Concerning the impact of the present research activity, the developed algorithm aims at improving both the performance and the lifetime of an SOFC system by its implementation into a comprehensive control strategy. In this way it is possible to associate to the diagnosis of the system status specific counteractions performed by the system controller. In this way, both the manufacturer and the final users can obtain significant advantages in terms of management costs reduction (i.e. maintenance and materials costs) and overall efficiency increase.

To summarize, the main contributions and innovative features of this research activity are listed in the following:

- the development of a diagnostic algorithm following a model-based approach;
- the improvement of an FSM, based on an FTA, through the exploitation of fault models simulation to evaluate the sensitivity of the monitored variables to the faults magnitudes;
- the implementation of a statistical hypothesis test for the evaluation of false alarm and miss detection probability;
- the design of specific procedures and hardware modifications to mimic faults in a controlled way on a real SOFC system (i.e. the Galileo 1000N) for the diagnostic algorithm validation;
- the offline and the online validation of the proposed algorithm implemented on-board and controlled through a graphic user interface.

It is worth noting that the innovative features presented in this manuscript are a pioneering contribution in the available literature. Most of the results presented in this dissertation have been carried out within the framework of the European Project GENIUS (Generic diagnosis instrument for SOFC systems) and received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cell and Hydrogen Joint Technology Initiative under grant agreement N° 245128.

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