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Curriculum in Mechanical Engineering

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Design, development and on-field testing of advanced solutions for monitoring, diagnosis and fault mitigation of SOFCs

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ENGLISH ABSTRACT

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Abstract

The work presented in this thesis is aimed at developing an advanced algorithm to monitor the State of Health (SoH) of Solid Oxide Fuel Cells (SOFCs). Then a computational structure has been implemented for the diagnosis of fuel cells faults along with a set of strategies for mitigation actions. The main idea is to apply advanced methods based on Electrochemical Impedance Spectroscopy (EIS) for diagnosis. Then, EIS and Conventional approaches are used to infer on the SOFC system status and to predict its Remaining Useful Life (RUL). Moreover, all those approaches are applied to provide helpful guidelines on possible mitigation countermeasures to be actuated in case of faults.

SOFCs can play a beneficial role in the World's changing energy landscape, being one of the most suitable alternatives to conventional energy production systems for stationary power generation, co-generation and Auxiliary Power Unit (APU). In the last decade, the enhancement of these SOFC-based products has opened perspectives and opportunities that make them valid solutions to contribute to the energy decarbonization scenario. In Europe, their deployment is still limited by high manufacturing costs and limited lifetime due to faulty operations and degradation processes (i.e. leakage, carbon deposition, anode reoxidation, poisoning, etc.), which reduce cell performance during time and can lead to failures in the main components (i.e. the cells). As far as maintenance and warranty expenses are concerned, it is clear that increased reliability and lifetime will contribute to the reduction of SOFCs operating costs and their further market success.

The most common variables that allows faults detection and isolation in the system are mainly current, voltage and temperature. To extract additional information about the SoH of the system, V-I curves and Electrochemical Impedance Spectroscopy (EIS) methodology might help, focusing on the fuel cell electrochemical behaviour. Particularly, the EIS is an advanced diagnostic tool that supports in evaluating the SoH of the stack. It is linked with an Equivalent Circuit Model (ECM) to model the status of the system.

By comparing the data measured in nominal (i.e. unfaulty) conditions to those recorded while the stack is operating, it is possible to identify any change in the spectrum that can be associated to one or more faulty operations that triggers the effect of one or more degradation phenomena respectively. On the other hand, by monitoring the behaviour of the SOFC over time, it could be also possible to identify the impact of the arising degradation phenomena due to the ageing of the cell. In this work an Equivalent Circuit Model (ECM) is used to describe the main processes occurring within the cell and to extract quantitative information as fault and degradation metrics.

One of the results accomplished is the development of a completely generic algorithm named Matching Geometric Fitting Guess (MGFG), based on EIS for detection and isolation of faults in either single cells or stacks. The MGFG algorithm follows an ECM approach, then parameters extraction are performed by means of a UNISA proprietary patented technique. This allows high generalizability and fast fitting of the measured spectrum. The results achieved by applying such methodology to Proton Exchange Membrane Fuel Cells(PEMFC) spectra in the frame of the EU project HEALTH-CODE paved the path toward the application to SOFCs, of which this work aims at defining a general algorithm to extract useful metrics for diagnostic purposes.

The related features (i.e. the metrics themselves, their combination, or the parameters estimated from them) are properly selected as sensitive indicators of the cell/stack State of Health (SoH) and then used to infer on their status. The whole methodology developed was tested and validated upon experimental data coming from the EU projects INSIGHT and SOSLEM. By combining the information derived from ad-hoc experiments with the heuristic knowledge on the phenomena of interest, a Fault Signature Matrix (FSM) was built to correlate the faults to the

symptoms observed during the online monitoring of the stack.
For the purpose of this thesis, fuel starvation phenomenon was considered as fault and the related FSM was populated accordingly. Thresholds were set upon experimental evidences on segmented cells, short stacks and full stacks; then the diagnostic approach was validated on all these configurations as well.

The study on stack ageing towards lifetime estimation was performed via lumped modelling approach and the related validation was carried out with respect to experimental data. This allows simulating the expected nominal conditions, as unfaulty and nominal reference states for the monitoring. Then, a stack aging submodel was implemented by integrating some ECM-based extracted features, enabling the simulation even during natural degraded operations. The results led to a RUL estimation model, successfully validated upon experimental data.

The fault mitigation was investigated to define possible countermeasures to be actuated when a fault occurs. Particularly, the inference on experimental faulty data, provided by the INSIGHT project, and its matching with the heuristic knowledge led to the development of a general methodology for fault mitigation countermeasures.
Moreover, a study was performed to define a sequence of actions that led to a flowchart for maintenance able to support the users to either stabilize or recover the stack from the fault. From the same study the specifications for a mitigation algorithm can be derived as well. Here, the diagnostic algorithm and the related extracted features are used in a kind of "reverse mode" to provide information about the feasibility and effectiveness of the countermeasure applied. In this work the Fuel Starvation case was analysed and the related flowchart was drafted.
Finally, a methodology that combines the diagnostic techniques and a mitigation-oriented control approach was proposed. A case study for fuel starvation caused by hydrogen leakage was performed and the results for the fault mitigation feasibility were discussed.

In summary, a EIS-based algorithm was developed and applied to detect fuel starvation in solid oxide fuel cells and stacks. A lumped dynamic model successfully simulated the ageing of such systems, aiming at lifetime estimation. Useful mitigation guidelines were provided to increase the market deployment of these devices. These results paved the way for further work aiming at increasing the Technology Readiness Level (TRL) of such Monitoring, Diagnostic and Lifetime Tool (MDLT) for commercial purposes along with a prognostic field to be investigated.

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