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Health and conditions monitoring for PEMFC automotive systems: towards on-board, online and near real-time EIS based diagnostics

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Abstract

Decarbonizing automotive sector is challenging, especially in heavy-duty and long-haul segments, where range, refuelling time and energy-density constraints limit direct electrification. This is accelerating interest in hydrogen and Proton Exchange Membrane Fuel Cell (PEMFC) powertrains; however, large-scale adoption still requires higher efficiency, durability and reliability under highly variable operating conditions, governed by tightly coupled electrochemical and transport phenomena that are not directly observable. Consequently, research is advancing stack materials and architectures, improving balance-of-plant efficiency and developing diagnostics to extend lifetime and reduce cost. Yet, current on-board monitoring is still largely limited to high-level signals which provide only partial visibility of the internal health and performance status of PEMFCs. The aim of this thesis is to bridge this gap by providing the basis for a Health Monitoring Unit (HMU) capable of operating on-board, online and in near real-time. To achieve this, the proposed approach is based on Electrochemical Impedance Spectroscopy (EIS), as it offers details of internal electrochemical and transport processes. EIS is traditionally performed in laboratory by applying periodic current or voltage perturbations over a range of frequencies, measuring the response, and post-processing the data to obtain an impedance spectrum. However, scaling EIS to automotive use faces three key barriers: (i) long acquisition time at low frequencies when using conventional sine excitation (at least 10 s to acquire a single point at 0.1 Hz), (ii) complex interpretation since information is commonly extracted by fitting Equivalent Circuit Models (ECMs) whose structure is not unique and (iii) the cost and size of lab-grade instrumentation, whereas automotive integration requires minimal additional hardware. This thesis addresses these limitations by developing an HMU composed of three fundamental blocks. (1) The Excitation Signal Generator (ESG) defines fast excitation signals suitable for on-board implementation. Several candidates were investigated with a focus on reducing measurement time while maintaining spectral fidelity. (2) The Frequency Response Analyzer (FRA) post-processes raw current and voltage to reconstruct the impedance spectrum, using signal-specific methods optimized for both noise robustness and low computational cost. (3) The Impedance Analysis Tool (IAT), which is the core of the data analysis methodology, combining Distribution of Relaxation Times (DRT) concepts with ECM-based processing to extract standardized, physically meaningful features and translate them into fault and

health indicators. The HMU blocks were validated through an extensive experimental campaign on PEMFCs assembled and tested in the laboratory. For the ESG, the selected fast excitation reduced the acquisition time from minutes to on the order of 10 s and was benchmarked against the standard sine-sweep, showing excellent agreement between the resulting impedance spectra. The FRA reconstruction was also validated against a lab-grade EIS instrument, demonstrating high accuracy. The IAT was validated on a database of optimal and faulty operating conditions, confirming both the assignment of the underlying physical processes (automated with machine-learning algorithms) and their correlation with fault indicators. Drying and flooding indicators consistently tracked relative humidity changes, while the starvation indicator responded correctly to variations in stoichiometry. Accelerated stress tests were also conducted, but premature pinhole failures prevented the definition of reliable health indicators. Finally, a physics-based impedance model provided theoretical validation, showing good agreement between analytical process resistances and those extracted by the IAT. To assess real-world feasibility, the HMU was evaluated in Software-in-the-Loop and Processor-in-the-Loop. Computation time was negligible in SiL and less than 5 s on the PiL hardware, nevertheless, the IAT accuracy was slightly lower in PiL, likely due to embedded numerical precision constraints. Finally, on-board EIS was explored and based on literature architectures, a converter-based excitation strategy was simulated using a controlled DC/DC converter and the FRA was tested for impedance reconstruction, demonstrating the feasibility of integrating EIS excitation within existing power electronics. In conclusion, the research establishes the foundations for a reliable HMU suitable for online, near real-time, on-board deployment, enabling fault isolation in approximately 15 s precisely about 10 s for voltage and current acquisition and roughly 5 s for post-processing.