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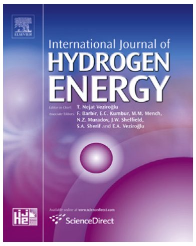

A Petri net approach for performance modelling of polymer electrolyte membrane fuel cell systems

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ABSTRACT

Fuel cells are promising technologies for zero-emission energy conversion and power generation. However, durability and reliability are among the main barriers to their commercialisation. Clearly the system performance depends on the reliability of the overall system including both the stack and the balance of plant. This paper seeks to introduce a modelling approach based on the Petri net method for the performance analysis of fuel cell systems. The proposed Petri net model intends to simulate the operation of the fuel cell stack and its supporting system to predict the system performance based on the system structure, along with the components deterioration process. The model considers the causal relationship between the operation of the balance of plant and the fuel cell stack performance. Purging is performed periodically in order to restore some of the voltage loss due to water accumulation or impurities within the cell. Failures of single components of the supporting systems are considered, which will have an immediate effect on the output voltage as well as long term effects on the stack performance.

Introduction

Reducing carbon emission by developing innovative, high quality and highly reliable low emission power generation sources is a main aim of the UK energy sector in order to meet the UKs Climate Change Act (2008) target to reduce emissions by 80% by 2050. In this context hydrogen and fuel cells are promising technologies for zero-emission energy conversion and power generation. Fuel cells are electrochemical devices that convert the chemical energy of a fuel into electrical energy by reaction with oxygen or other oxidising agents. As a result of the chemical reactions taking place within the cell, electrical energy is produced along with heat and water. Fuel cell technologies are suited to a wide range of applications, from portable to transport and stationary systems. In order to meet the power demand of a given application, single cells are connected in series to form a stack. The stack is only the core of a wider system supporting the stack operation, including equipment for storage and supply of reactants, cooling and water management system, power conditioning and a control unit. High costs, short lifetime, durability and reliability are the main barriers to their commercialisation. Quantifying the long-term performance and durability of fuel cell is difficult because of the lack of a deep understanding of the deterioration processes occurring within the cell. Lifetime, durability and performance requirement of fuel cells stacks vary with the application. The required lifetime of fuel cells stacks range from 3000/5000 operating hours for automotive applications, up to 40,000 h for stationary applications [1,2]. However, the

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Nomenclature

MTTF	mean time to failure
MTTR	mean time to repair
η	scale parameter of the Weibull distribution
β	shape parameter of the Weibull distribution
γ	location parameter of the Weibull distribution

lifetime of a fuel cells stack is difficult to estimate; standard engineering measures of lifetime such as mean time to failure (MTTF) are difficult to specify since fuel cell's performance degrades gradually due to the ageing of its components and degradation rates strongly depend on the cell operating conditions. The gradual decline of voltage is usually given in units of millivolts per 1000 h and an average degradation rate range of 1–10 μV h^{-1} over the entire lifetime is commonly accepted for most applications [1]. The fuel cells stack is considered to fail whenever it is not able to provide the required power output, either temporarily and permanently, in which case the stack needs to be replaced. The purging of the stack is performed periodically in order to eliminate impurities and water accumulated inside the stack and therefore to restore the reversible voltage losses.

Very little information on polymer electrolyte membrane (PEM) fuel cell systems reliability is available in the literature. In Ref. [3] Feitelberg discusses the field reliability of a fleet of PEM fuel cell systems developed over a period of three years and shows its improvement by means of a combination of hardware and software changes to the original product. The authors provide the most frequent causes of failure observed and specify that the stack contributes to failure more than any other component. Literature on modelling of fuel cell reliability is still at its infancy and is mainly focused on the application of fault tree analysis. A fault tree is a top-down representation of the state of the system given in terms of the state of its components. Placca [4] performs a fault tree quantitative analysis for modelling degradation mechanisms affecting a single PEM fuel cell. The authors construct quantitative fault trees listing the basic events leading to degradation of the membrane, the catalyst layers and the gas diffusion layers. Degradation rates are collected from the literature and specified for each basic event, along with the test conditions in which those degradation rates were obtained. However, the data used refer to different materials, operating conditions and test methodologies and therefore are subjected to uncertainty. Yousfi-Steiner [5] uses fault tree analysis to gain a better understanding of PEM degradation associated with water management. Water management has a determining impact on fuel cell performance, compromising cell stability, reliability and durability. The authors classify the failures related to improper water management into two groups: flooding and drying out. The authors review in detail the influence of operating conditions and parameters, concluding that gas flow rate, relative humidity, temperature and current density have a major effect on water balance. Then they build simplified fault trees where variations of the aforementioned parameters are given as basic event for flooding and membrane dry-out issues. Rama [6] provides a structured review of the degradation processes occurring within PEM fuel cells and leading to performance losses and cell failures. Causes and effects of degradation mechanisms and failures are systematically organized in terms of irreversible increase of activation losses, ohmic losses, mass transportation and efficiency losses. For each loss mechanism the authors provide a table detailing the components involved, the fault as well as the cause. In Ref. [7] the authors translate the failure mode and effect analysis performed in their previous work into fault tree diagrams. The degradation mechanisms that induce performance losses are organized into five fault trees. Each diagram depicts how basic events involving the different fuel cell components can develop into each of the five losses mechanisms (activation, ohmic, mass transportation, efficiency losses and catastrophic cell failures). Although fault tree diagrams can provide a list of causes leading to cell degradation, this analysis technique is not capable to reproduce the complexity of the degradation mechanisms leading to performance loss. Fuel cells loss of performance and failures are the result of continuous degradation processes. Degradation rates can vary drastically depending on the concurrency and combination of different operating conditions, and fault tree diagrams do not catch those dependencies between events and influencing factors. In order to account for data unavailability and uncertainty, Mangoni [8] suggests a probabilistic approach to evaluate the reliability of a single PEM fuel cell. The reduction of power output is modelled as a random variable described via a beta distribution. Tanrioven [9] presents a state-space method for modelling reliability of PEM Fuel cell power plants. In particular the authors use the Markov state-space equation to calculate system reliability. The Weibull distribution is used to generate transition rates, while fuzzy logic is applied in order to estimate the state of health of the auxiliary components during operational lifetime. Mathematical models based on mechanistic and empirical approaches have been used in the literature to predict both the steady-state and the dynamic performance of a single fuel cell or a stack. In order to compute the stack (or single cell) voltage, most of these models make use of empirical equations providing the voltage variation vs the current based on observation and data fitting of polarization curves. The most used empirical equation for the description of the voltage as a function of current density over the entire current density region was first introduced by Kim [10]. However, the coefficients appearing in those formulations depend on the operating conditions and therefore need to be re-evaluated for every change of the operational parameters.

This paper seeks at introducing an initial modelling method for the performance analysis of fuel cell systems including the stack and the supporting system. The model intends to simulate the operation of the fuel cell stack and its supporting system over the prescribed lifetime to predict the system performance based on the system structure and the components deterioration processes. The model takes into account the causal relationships between the operation of the balance of plant (BOP) and the fuel cell stack performance. Malfunctioning and/or failures of components of the BOP affects reactants flow, stack temperature, reactants and stack humidification level, causing the stack to operate under