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Fault tree analysis of proton exchange membrane fuel cell system safety

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ABSTRACT

Proton exchange membrane fuel cells (PEMFC) system is considered as a solution for electric vehicle autonomy. Hydrogen must be mastered to preserve safety. The risk associated with hydrogen is a consequence of these properties. This study proposes a model of explosion for reliability analysis by fault trees. Details of the PEMFC system architecture are taken into account. The data used are from professional database. Adaptation of these data is proposed to reflect the actual conditions of use of a PEMFC system and a model of degradation mechanism which is realistic. The probability calculation is performed in relation to a reference time of use. The probability of explosion of the system is thus evaluated and critical failure sequences are identified. For these minimum critical cut that are dependent on degradation due to the use of the system, inverse calculation are proposed to define the targets of the design by reliability.

Introduction

Development of system of proton exchange membrane fuel cell (PEMFC system) to automotive industry is on track. As of now, designers are implementing first series of vehicles with PEMFC systems. These first vehicles must comply with the safety integrity obligations. Indeed, safety is a major user expectations of automotive vehicles [1,2].

PEMFC requires a great number of auxiliaries. This article takes into account the overall PEMFC system. Our system is composed of a stack, a hydrogen supply, a supply of air coupled to a humidification circuit, a cooling circuit, an electric converter, and a control system. Integrating a PEMFC system in a vehicle presupposes an embedded storage sufficient amount of hydrogen to its autonomy. The associated risk with the hydrogen is a consequence of these flammability properties and high amount of energy released by explosion [3,4]. Several studies propose approaches for risk analysis of hydrogen systems [5].

Safety analysis of PEMFC system is performed according to an approach that incorporates the life cycle of the system. The process of design and implementation of technological solutions is called dependability [6]. It allows you to place confidence in the choice adopted. Systems safety are part of a process of systems dependability (reliability, avaibility, maintainability and safety). High safety of the PEMFC is not without the safety analysis of its auxiliaries [7]. PEMFC system is complex, so it is necessary to focus efforts on the most critical points. It is therefore necessary to focus studies in

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order to improve effectively the safety of PEMFC system. The application is presented for the integration of a PEMFC system inside electric vehicles.

There are several methods to model the dependability and particularly systems safety, as detailed in Ref. [6] such as fault tree [8], Markov chains or Petri net [9,10], Bayesian networks [11]. O. Rosyid and et al. [12] use a fault tree to model a tank rupture in a hydrogen station storage. Rodionov and et al. [13] use event tree to analyse effects, as hydrogen explosion, of car accidents with collision or fire on a fuel cell (FC) vehicle.

This article focuses on a risk assessment of explosion caused only by internal failures of PEMFC system during normal operation. It is a contribution to the modelling of intrinsic failures that can lead to an explosion using fault tree analysis. This present work assesses weaknesses of a fuel cell system. Also it allows to fix reliability requirements on fuel cell safety system.

Next section describes the PEMFC system studied and the methods used. Then, the fault tree leading to the explosion is presented. The results of applications of the fault tree are presented in section 4.

PEMFC system and methods

The PEMFC system considered

The PEMFC system is installed in a fuel cell-battery hybrid automotive vehicle. A *Range Extender* architecture is often used thanks to development of battery and FC technology for the automotive industry. As for several existent engineering solutions [14,15], this system consists on a 5 kW stack power. The PEMFC used contains 64 cells. It is well known that the operation of a PEMC also depends on proper operation of all these auxiliaries [7]. That is why we study the PEMFC system as a whole. The principle of operation is classic. It is described in many articles [16]. An air circuit, with an air compressor, feeds an input of the stack. An hydrogen circuit, with a 350 bar hydrogen tank, feeds second input of the stack. The PEMFC is cooled by a water cooling system. At its output, the PEMFC is accompanied by an energy conversion. A system for detecting leakage of hydrogen provides some safety functions. Finally, a controller manages all sub-systems. Fig. 1 presents hydrogen circuit of the PEMFC system.

Focus on hydrogen circuit

The hydrogen tank is equipped with a thermally activated pressure relief device (TPRD). This TPRD safety valve is connected to an outlet for discharging the contents of the tank to the outside of the vehicle. The opening of the tank is controlled by a cut off valve. The gas expansion is carried out by two pressure regulators. The first one is located at the tank outlet (High pressure to medium pressure (PrHM) regulation). The second one is at inlet to the stack (Medium pressure to low pressure (PrML) regulation). Periodic purges evacuate small quantities of hydrogen by an exhaust of the vehicle outwards. Two hydrogen sensors are arranged inside the atmosphere of PEMFC system to prevent abnormal hydrogen rate caused by leaks. A fan can ventilates atmosphere of PEMFC system.

The analysis approach

Safety analysis accompanies the system throughout its life cycle. This study focused on the use of life step of the system during operation of the vehicle. Filling steps are not taken into account. Several analysis tools are used to ensure its operation safety [6,17]. This approach aims to control failures that can occur and cause of dangerous events. Most studies dependability are however carried out during the design phase of the system [18]. They follow a structured approach (Fig. 2).

This approach begins with the functional analysis of the system. Functional safety of the PEMFC is incorporated there. To do that a preliminary risk analysis was lead on the system studied. It completes the specifications by the safety goals. J.-B. Saffers and et al. [19] proposes a risk analysis of the hydrogen system that can also be used.

The analysis of the functioning studying how the proposed solution can meet the essential functions identified in the functional analysis. In other words, how each of the specifications identified above are they insured by the organs of the system. Based on this analysis of the functioning of the PEMFC system, dysfunctions and failures could be identified. The evaluation of these problems is the object of quantitative analysis of the system.

The failure analysis of PEMFC system research sources (causes) of system and their consequences (effects). Two large families of analyses are commonly used. Some inductive (such as hazard and operability study (HAZOP) or analysis of

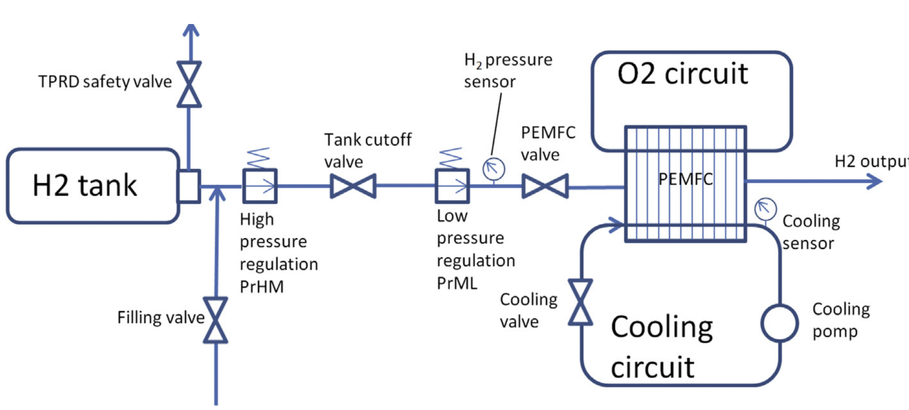

Fig. 1 – Hydrogen circuit of the PEMFC system.