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Determination of the predictive Reliability for PEMFC system

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***Abstract*—Today reliability is one of the serious requirements of fuel cell systems, and their associated cost in all applications, in general, and automotive applications, in particular when the power requirement is scaled up, is still unclear. Therefore, increasing cell lifetimes and membrane electrode assembly (MEA) durability is the technical advance that may be expected so that we can have a remarkable tendency of decreasing in fuel cell costs with a significant increase in global systems safety, that best meet customer requirements. Our contribution, in this paper, it focuses on the simulation method of the "Monte Carlo" over the entire reliability calculation for PEMFC system, with integration of the most critical elements of them and proposition of the contrivances for their modifications, in the objective to predict the lifetime and failure rate of a system by reliability calculations: a problem formulation is given, a reliability calculations of PEMFC is defined and a reliability estimation methodology is developed. We did obtain, however, some results that can help us in the prediction reliability way at the design phase, which are outlined and introduced as a conclusion.**

Keywords*— *Reliability; PEMFC; Boost; Buck; Batteries; Fides; MIL-HDBK-217.

I. INTRODUCTION

In near future, fuel cells could provide an attractive value proposition, particularly for economic and environmental reasons. They are highly efficient, low fuel consumption, produce minimal or no harmful emissions very low noise and have relatively low maintenance requirements [1]. In the past few years, an advanced effort through international research and development activities on fuel cell systems technologies for various applications has dramatically been increased [2]. In the same vein, the polymer electrolyte membrane fuel cell (PEMFC) has been regarded as a promising power source, especially for transportation and stationary cogeneration applications due to its high efficiency conversion, low-temperature operation, high power density, fast startup, and system robustness [3].

The However, to implement them in transportation systems, their durability and their reliability should be improved. For this purpose, many studies were done on the durability and reliability of PEMFC [4]. Concerning fuel cell reliability, this conceptual notion which refers to the ability of a fuel cell or stack to perform the required function under stated conditions for a period of time, Fowler et al., (2002; 2003) [5-7] concluded that the voltage degradation will be the main factor governing the life of the stack, and for that reason they introduced two new terms to account for membrane electrode assembly (MEA) ageing, specifically the ageing of the MEA materials, so that they can be analysed with the changes in the polarization curve predicted by the Generalised Steady State Electrochemical Degradation Model (GSSEDM), a conceptual model for fuel cell stack reliability which has been developed for the first time [8]. Afterwards, Tanrioven and Alam (2006) [9] developed a state-space generation model for a stand-alone PEM fuel cell. Mangoni et al [10] have developed a stochastic model to assess the reliability of PEMFC, the model introduces the use of random variables in the reliability assessment, and proposed a reliability evaluation algorithm as a tool to facilitate maintenance scheduling of PEM replacement. Gerbec et al., (2008) [11] presented an analysis with a hazard and operability (HAZOP) study, a failure-scenarios' development and a fault-tree analysis (FTA) using equipment-failure-rate data in (changes/improvements) with respect to the (reliability/availability), maintainability and safety aspects of a commercial and transportable PEMFC system rated at 7 kW nominal power. Wieland et al., (2009) [12] modeled PEMFC stacks and its behaviour over time by a Petri net by the mean of a model which computes reliability data of PEMFC stacks, especially the average lifetime of a single stack or the reliability of stacks of a whole fuel cell vehicle fleet within a given timing. In (2010), Frappe et al., [13] have presented a fault detection and identification methods which is applied to a single cell up to multi-cells stacks used for power applications like transportation, with using simple and non-intrusive on-line monitoring techniques. Khayyer et al., [14] have presented a reliability analysis for a new advanced system configuration with two downsized fuel cells, the reliability of this system configuration is investigated and compared with conventional designs of hybrid fuel cell vehicles.

Taking into account previous recent works in this direction, where, the performance stability and reliability of fuel cell systems appears to be an extremely important issue. If we take as an example some works: Zheng et al,. (2013) [15] indicated that to realize commercialization of PEMFCs, durability and reliability remain large challenges. Although the PEMFC technology is maturing towards large-scale commercialization; the two issues (durability and reliability) have become great challenges as was mentioned in an academic study that was presented by Abhijeet Gajanan Phalle (December 14, 2013) [16]. Currently in the European Fuel Cells and Hydrogen Technology Initiative, the reliability present one of the main keys to strengthening fuel cell technology performances and which will allow their market introduction [17]. Despite the various works that are interested in this issue, the majority of this research focuses on a specific part of components of fuel cell stack/system. Therefore, a simulation method of the entire fuel cell system is necessary for obtain a better understanding and evaluate the potential failure of the system to continuous operating times. In following the works of Whiteley et al. (2013) [18] studied the possibility of using the reliability analysis techniques such as Fault Tree Analysis (FTA) to gain a greater understanding of the failure modes in a PEMFC and their relationships, our contribution is interested in the simulation method of the "Monte Carlo" over the entire reliability calculation for PEMFC system, with integration of the most critical elements of them and proposition of the contrivances for their modifications.

II. PROBLEM FORMULATION

More papers have been published considering the fuel cell (FC) operation in normal conditions; but much less of them addressed the FC operation under fault conditions. Faults are events that cannot be ignored in any design for real machine, and quantify their consideration is essential for improving the performance in design of equipment based on fuel cell [19].

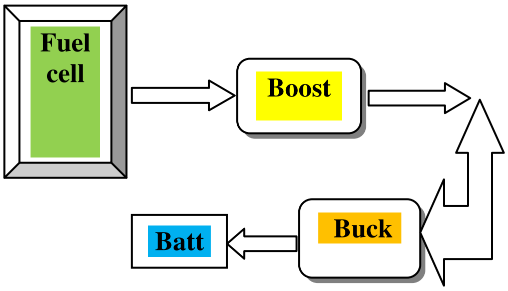

Fig. 1: PEMFC systems topology

The performance of a PEM fuel cell or stack is affected by many internal and external factors, such as fuel cell design and assembly, degradation of materials, operational conditions, and impurities or contaminants [20].

Performance degradation is unavoidable, but the degradation rate can be minimized through a comprehensive understanding of degradation and failure mechanisms [3].

III. RELIABILITY CALCULATION OF PEMFC SYSTEMS

III.1. Assessment of the reliability of the PEMFC

In this section a design approach performed with the identification of system components and failure modes and potential consequences. Then, the use of default probabilities for the various components of the system and the risk associated with a particular system design was determined.

Based on the study by [20, 21], supported by an overview of the various risks that may be present in cogeneration systems based on fuel cells.

From this conclusion, we used the calculations presented in this study:

a) The probability was used as an overall system value. All products degrade in a finite time, the probabilities are presented as functions of time and the sum of the probabilities of failure and luck $P_{défaillance}$,P_{chance} is equal to unity .

$$p_{défaillance}(t) + p_{chance}(t) = 1 \qquad (1)$$

b) The formula for the probability of luck (or the reliability R) is usually written as :

$$R = p_{chance} = e^{(t \times \frac{fpmh}{10^6})} \qquad (2)$$

With $$fpmh = \frac{10^6}{MTBF}$$

Where MTBF is the average time characterizing the failure. (Mean time between failures).

TABLE 1

BELOW SUMMARIZES THE DIFFERENT VALUES

OF THE PARAMETER OBTAINED FOR SEVEN *fpmh*

Variable	Component Name	Subsystem	# de Comp.	Median *fpmh*
pc1	MEA	Fuel Cell	80	200
Pc2	Diffusion layer	Fuel Cell	160	100
Pc3	Bipolar plates	Fuel Cell	81	0.1
Pc4	Gaskets	Fuel Cell	160	0.0597
Pc5	Reinforcing rods	Fuel Cell	12	2.7835
Pc6	Nuts	Fuel Cell	12	0.5744
Pc7	Connectors	Fuel Cell	3	5.9243

Using equation (2) and the parameter values of the failure rate, one can estimate the reliability of each component:

TABLE 2

VALUES R_{COMP} THE ESTIMATED COMPONENTS

OF THE STACK CESHR

	R_{comp}, t=0	R_{comp}, t=2000h	R_{comp}, t=4000h	R_{comp}, t=6000	R_{comp}, t=8000	R_{comp}, t=10000	R_{comp}, t=12000	R_{comp}, t=24000	R_{comp}, t=50000
Estimated reliability of each component									
MEA	1	0.670	0.449	0.301	0.201	0.135	0.009	0.009	0.000051
Diffusion layer	1	0.8187	0.670	0.5488	0.449	0.367	0.301	0.301	0.0067
Bipolar plates	1	0.9998	0.9996	0.9994	0.9992	0.9990	0.9988	0.9988	0.9950
Gaskets	1	0.9998	0.9997	0.9996	0.9995	0.9994	0.9992	0.9992	0.9970
reinforcing rods	1	0.9944	0.9889	0.9834	0.9779	0.9725	0.9671	0.9671	0.8700
Nuts	1	0.9988	0.9977	0.9965	0.9954	0.9942	0.9931	0.9931	0.9716
Connectors	1	0.9882	0.9765	0.9650	0.9537	0.9424	0.9313	0.9313	0.7436

III.2 Estimation of the reliability of auxiliary

We present here details of the calculation of rates of individual component failure used in auxiliary system PEMFC stack to MIL-HDBK- 217F [22] specifications and FIDES .

Collections reliability is built from data returned from experiences, and to define the probability of component failures.
These codes are based on the assumption that the failure rate is constant throughout the life of the component (no effect related to aging.) For this study, we selected the most commonly used codes, may be able provide relevant results for power electronics: MIL-HDBK- 217F and FIDES.

III.2.1. Presentation model for calculating the reliability

III.2.1.1. Model MIL -HDBK- 217F:

The first aim of this collection was to establish a method of estimating the reliability of electronic equipment and military systems. Today despite the obsolescence of its data, and the fact that he no longer has been updated for more than ten years, it is still widely used in many industrial fields [23].

The assessment rate of failure of a component λP is based on the following principle:

$$\lambda_P = \lambda_b . \pi_T . \pi_C . \pi_S . \pi_R . \pi_Q \pi_E \quad \text{Failures}/10^6\text{h} \qquad (3)$$

λb is the failure rate of the base component (expressed from a classical model such as exponential law), while π factors reflect constraints such as the temperature of the job, the electric stress, the quality of manufacturing, environmental constraints, etc. The calculation of failure rate of a map is based on a series of model components considered.

III.2.1.2 Model FIDES:

The reliability of FIDES approach is based on the consideration of three components: technology, process and use. These components are considered for the entire life cycle from product specification phase to the operational phase and maintenance [24].

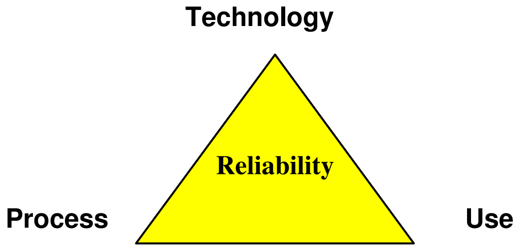

Fig. 2: Representation of FIDES model

The general model of reliability FIDES an article based on the following equation:

$$\lambda = \left(\sum physic \cdot contrubitions\right) \times \prod process \cdot contubitions) \qquad (4)$$

Where:

- λ is the failure rate of the item.
- Σ $_{\text{Process Contributions}}$ represents a term mainly additive construction, which represents the physical and technological reliability contributions.
- Π $_{\text{Process Contributions}}$ is a multiplicative term process that represents the impact of the development process, production and operating reliability.

In practice, this equation becomes:

$$\lambda = \lambda_{PM} . \prod \Pr ocess \qquad (5)$$

Where:

- λ Physique represents the physical contribution.
- ΠPM (PM for Part Manufacturing) reflects the quality and technical mastery of manufacturing the article.
- Π Process reflects the quality and technical mastery of the process of developing, manufacturing and use of products containing the article.

The reliability assessment is possible with different levels of finesse to match the progress of the projects:

- detailed, most complete method.
- Counting Method reliability by types of articles.
- The easiest method to apply reliability by counting families articles.

Methods by counting reliability types of articles and products families are derived from the complete detailed method. All general models apply equally to three methods that differ only by the level of information about the product it is necessary to treat.

III.2.2. Application of the calculation models of the reliability

The method of construction and evaluation of the reliability prediction is applied to the auxiliary cell PEMFC system.

a) Calculation of failure rates from MIL HDBK-217F specification:

The calculation method and detailed results are given.

- *Calculating the failure rate of components Boost chopper*

TABLE 3

RATE COMPONENT FAILURE OF BOOST

	λ_b(FIT)	**π_Q**	**π_E**	**π_T**	**π_C**	**π_V**	**π_S**	**π_P**	**λ_C(FIT)**
D	0.0038	8	1	1.6	1		0.19		0.0092416
C	0.00051	3	1	1.6	1.047	59	3.3		0.0028820
L	0.000030	1	1	1.4					0.000042
R_C	0.0037	10	1	1.5			1.2	0.76	0.050616
R_L	0.0037	10	1	1.5			1.2	0.76	0.050616
R_{Ld}	0.0017	10	1	1.5			1.2	0.76	0.023256
S	0.60	1	1	1.4					0.84

The obtained results are provided in table 4.

TABLE 4

RECAP. RATE COMPONENT FAILURE OF BOOST

N°	**Designation**	**Number**	**λ F/10^6**
1	Diode (D)	1	λ_D=0.0092416
2	Capacitor (C)	1	λ_C=0.0028820
3	Inductor (L)	1	λ_I=0.000042
4	Resistor Rc	1	λ_{Rc}=0.023256
5	Resistor R_L	1	λ_{RL}=0.050616
6	Resistor R_{Ld}	1	λ_{RLd}=0.023256
7	Switch (Sw)	1	λ_{Sw}=0.84
λ_{Boost}			0.9548376
MTBF			1047339.75h/*f*

It is found that the reliability of operation of the boost chopper is 0.99 to 8000 hours of operation.

- *Calculating the failure rate of components Buck chopper*

TABLE 5

RATE COMPONENT FAILURE OF BUCK

	λ_b(FIT)	**π_Q**	**π_E**	**π_T**	**π_C**	**π_V**	**π_S**	**π_P**	**λ_C(FIT)**
D	0.0038	8	1	1.6	1		1		0.04864
C	0.00051	3	1	1.6	1.67	59	3.3		0.795964
L	0.000030	1	1	1.4	π_C				0.000042
R_C	0.0017	10	1	1.5	1		3.4	1.3	0.11271
R_L	0.0037	10	1	1.5	1.67		3.4	1.3	0.24513
R_{Ld}	0.0017	10	1	1.5	π_C		1.2	0.76	0.023256
S	0.60	1	1	1.4	1				0.84

The obtained results are provided in table 6.

TABLE 6

RECAP. RATE COMPONENT FAILURE OF BUCK

N°	Designation	Number	λ F/10^6
1	Diode (D)	1	λ_D=0.04864

2	Capacitor (C)	1	λ_C=0.795964
3	Inductor (L)	1	λ_I=0.000042
4	Resistor Rc	1	λ_{Rc}=0.11271
5	Resistor R_L	1	λ_{RL}=0.24513
6	Resistor R_{Ld}	1	λ_{RLd}=0.023256
7	Switch (Sw)	1	λ_{Sw}=0.84
λ_{Buck}			2.275046
MTBF			439560.44h/f

It is found that the reliability of operation of the buck chopper is 0.94 to 8000 hours of operation.

b) Calculation of failure rates from FIDES specification

- *Calculation of the battery failure*

General pattern associated with the family

$$\lambda = \lambda_{Cst} + \lambda_{vieillessement} \qquad (6)$$

With:

$$\lambda_{Cst} = \lambda_{Physique} \times \lambda_{PM} \times \lambda_{\Pr ocess} \qquad (7)$$

And

$$\lambda_{vieillesse\,ment} = \lambda_{à-batterie} \times .N_{cellue} + \sum_{i}^{phases}\left(\sum_{i}^{phases}\frac{t_{anuel}}{8760}\right)_i \times \left(\prod{}_{Thermique} + \prod{}_{TCy} + \prod{}_{Mécanique}\right)_i \times \left(\prod{}_{Induit}\right)_i \qquad (8)$$

After the calculation, based on the collection Fides 2009, one can find:

TABLE 7

RECAP. RATE COMPONENT FAILURE OF BATTERY

λ_{Physic}	λ_{PM}	$\lambda_{Process}$	λ_{Cst}	$\lambda_{vieillessemt}$	λ battery (FIT)
1.748	0.36	2.5	1.5732	$0.43X10^4$	4301.57

It has been found that the reliability of operation of the battery is 0.99 to 8000 hours of operation.

IV. RESULTS AND DISCUSSION

From these data, we have plotted the following graphs showing the reliability (probability of luck) versus time:

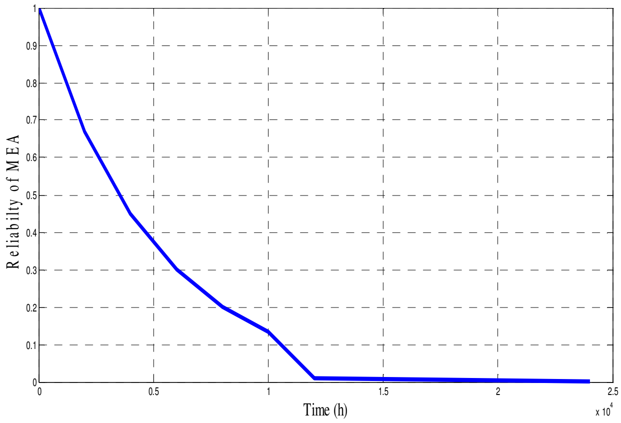

Fig. 3: Electrode assembly a membrane-electrode

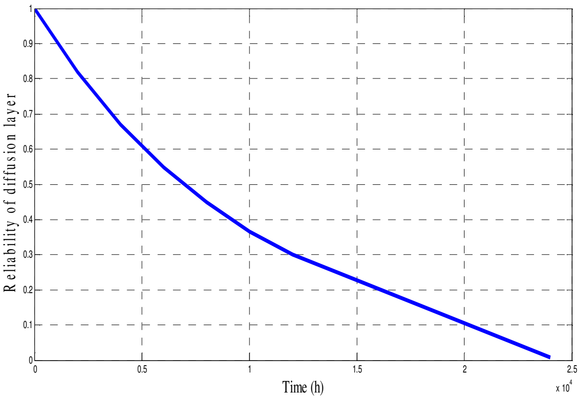

Fig. 4: The diffusion layer

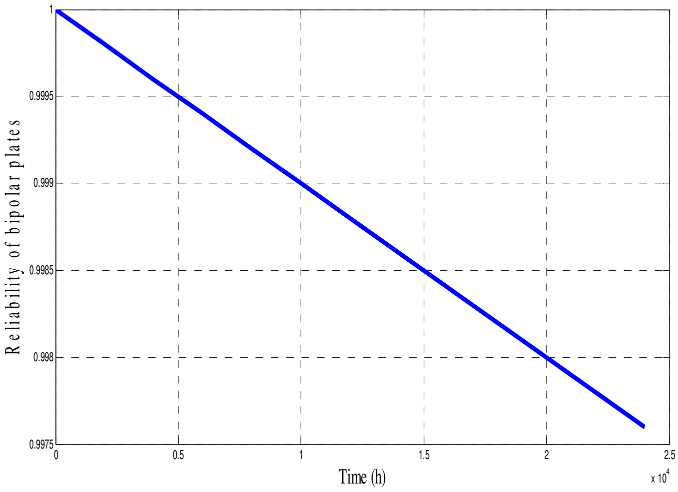

Fig. 5: Bipolar plates

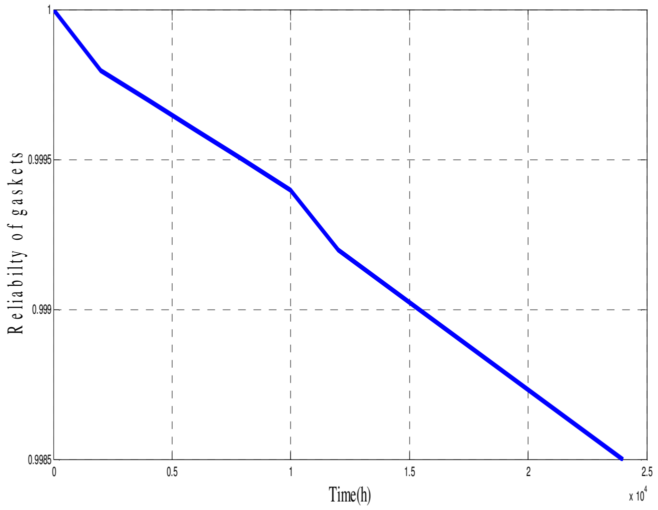

Fig. 6: Gaskets

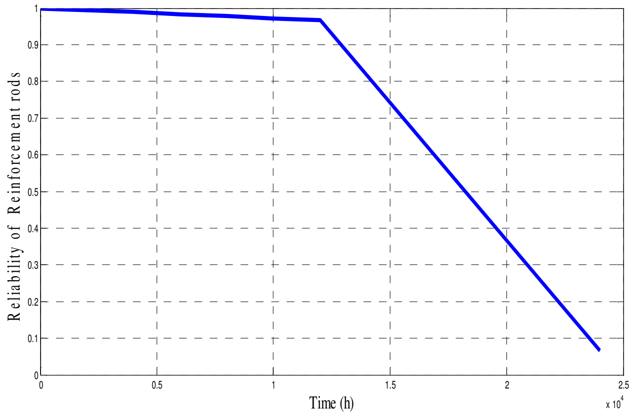

Fig. 7: Reinforcement rods

A simulation method of the “Monte Carlo” over the entire reliability of the system was used to evaluate the potential failure of the system to a continuous operating time of 5 hours, 10 hours, 50 hours, 100 hours and 500 hours. The initial system was tolerable but the initial time after 100 hours is capable of failure.

Analysis of the results shows that the electrode-membrane-electrode assembly (MEA) has suffered a failure rate of 50% after 3400 hours of operation and an almost total failure after 11,000 hours. In return, testing the lifetime of a PEMFC stack for space applications running on hydrogen and pure oxygen [25] have very ambitious results , a degradation rate of less than 2 microvolts / hr without loss of operation time for 11000 hours. Diffusion layers have suffered a failure rate of 50% after 7000 hours. Bipolar plates and gaskets have suffered a failure rate of 0.1 % after 11,000 hours of operation.

It is found that the reliability of operation of the PEMFC is 0.836 to 8000 hours of operation.

After a series of simulations that have been running for several alternative systems to provide suggestions for risk management by the "feedback" control , the main recommendation is that the process of risk engineering developed in this research is applicable to n ' any system and facilitates the use of many tools of engineering different risks [21]

V. CONCLUSION

The reliability and lifetime of the fuel cell operation are important considerations for the commercialization of fuel cell power sources. But also the total safety of this source is the element that determines its success in applying. However, so far the work of the scientific literature is limited to the failure modes of PEM fuel cells, the causes and mechanisms of degradation are not fully understood. In this paper we presented an overview of the main elements leading to the failure of a fuel cell.

In addition, the reliability of the prediction based on mission profiles systems design phase is a competitive advantage to the forefront as maintain system architectures that best necessary, ensuring mastery of new technologies introduced and realize innovative products with a sufficient level of maturity. The need for an industrial increase the reliability of power electronic systems is integrated needed to meet strong market demand.

Looking ahead, we intend to focus on the integration of this system into the world of automobile and do its optimization and control.

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