PREDICTION FAILURE FOR PEM FUEL CELLS

Vasile Anghel
National Centre for Hydrogen and Fuel Cell
National Research and Development Institute for Cryogenics and Isotopic Technologies
Rm.Valcea, Str. Uzinei nr.4, ROMANIA

ABSTRACT

A new conceptual methodology and some methods are used to predict failures that could potentially occur in Proton Exchange Membrane Fuel Cell (PEMFC) systems. The combination methods for prediction durability and safety for fuel cell design starting with matrices of technological process, function, components and requirements for PEM fuel cell systems. After input with characteristic date are applied adequate some methods like Failure Modes and Effects Analysis (FMEA), fuzzy method and Fault Tree Analysis (FTA) for prognostic and analysis failure for PEMFC system or/and components, like product or/and process. For application and solving objectives according to the methodology proposed, as a case study to consider the methods specified for fault prediction in a PEM fuel cell type, based on analysis of process parameters like pressure flow of hydrogen and oxygen (or air), electric voltage, electric current and the humidification of the proton exchange membrane. These variables determining the functioning of the fuel cell are adequately analyzed with Fuzzy Fault Tree method (FFT). Methodology algorithm is solved using LabVIEW software provided by the National Instruments. The proposed methodology is validated by specified references from scientific literature under experimental and modelling appearance.

KEYWORDS: *PEM Fuel Cells, Design, Durability, Reliability, FMEA*

I. INTRODUCTION

Fuel cells are an important enabling technology for the world's energy and have the potential to revolutionize the way we power our necessity, offering cleaner, more-efficient alternatives to conventional fuels. Fuel cells have the potential to replace the internal-combustion engine in vehicles and provide power in stationary and portable power applications because they are energy-efficient, clean, and fuel-flexible, but for that is necessary continuum scientific effort for overcome critical technical barriers to fuel cell market. Lifetime requirements by market fuel cell application. Required lifetimes must be achieved over a range of operational conditions, both expected and “out-of-spec”.

It is expected that in 2015 lifetime of fuel cell requirements for transportation applications are 5000 h (cars) and 20,000 h (buses), and for on-site cogeneration systems 40,000 h. Currently, the lifetimes of fuel cell vehicles and stationary cogeneration systems are around 1700 h and 10,000 h, [1].

Other key system attributes must be simultaneously satisfied. Current R&D focuses on the development of reliable, low-cost, high-performance fuel cell system components for transportation and buildings applications. However, several challenges still remain, including durability/reliability, cost, and performance, particularly for automotive and stationary applications. Durability has emerged as the top challenge.

PEM fuel cells consist of many components, including catalysts, catalyst supports, membranes, gas diffusion layers (GDLs), bipolar plates, sealings, and gaskets. Each of these components can degrade or fail to function, thus causing the fuel cell system to degrade or fail. Component degradation includes, but is not limited to, catalyst particle ripening, preferential alloy dissolution in the catalyst layer, carbon support corrosion, catalyst poisoning, membrane dissolution, loss of sulfonic acid groups in the ionomer phase of the catalyst layer or in the membrane, bipolar plate surface film growth, hydrophilicity changes in the catalyst layer and/or GDL, and poly tetra fluoro ethylene (PTFE) decomposition in the catalyst layer and/or GDL. It is therefore important to separate, analyze, and systematically understand the degradation phenomena of each component so that novel component materials can be developed and novel design for cells/stacks can be achieved to mitigate insufficient fuel cell durability.

The paper approach is based on a conception methodology (Figure 2), which allows adaptation of means (methods) to existing needs for continuous improvement type PEM fuel cell design. The goal is to predict possible failures due to an initial design and design review process in accordance with Figure 1. After input with characteristic date is applied adequate some methods like fuzzy method [24], and Fault Tree Analysis [25], Failure Modes and Effects Analysis (FMEA) [26], for prognostic and analysis failure for PEMFC system or/and components, like product or/and process. For application and solving objectives according to the methodology proposed, as a case study to consider the methods specified for fault prediction in a PEM fuel cell type, based on analysis of process parameters like pressure flow of hydrogen and oxygen (or air), electric voltage, electric current and the humidification of the proton exchange membrane. These variables determining the functioning of the fuel cell are adequately analyzed with Fuzzy Fault Tree method. Methodology algorithm is solved using LabVIEW software provided by the National Instruments. The proposed methodology is validated by specified references from scientific literature under experimental and modelling appearance.

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.

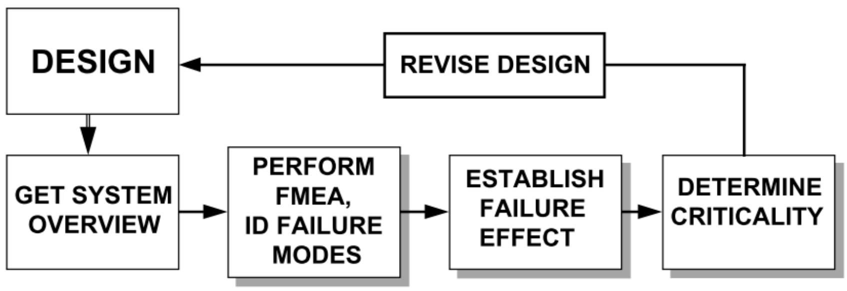


Figure 1. FMEA for revise design

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.

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

In order to clearly understand the concepts of PEM fuel cell lifetime and performance is better to first clarify several relevant terms [2–4]:

• Reliability: The ability of a fuel cell or stack to perform the required function under stated conditions, for a period of time. Combination of degradation, and failure modes that lead to catastrophic failure.

• Durability: The ability of a PEM fuel cell or stack to resist permanent change in performance over time i.e. degradation or irreversible degradation like as due to loss of electrochemical surface area, carbon corrosion, etc. This phenomena is related to ageing.

• Stability: The ability to recover function of efficiency, voltage or current density decay, reversible degradation or power lost during continuous operation. Stability decay is always concerned with operating conditions (such as water management) and reversible material changes.

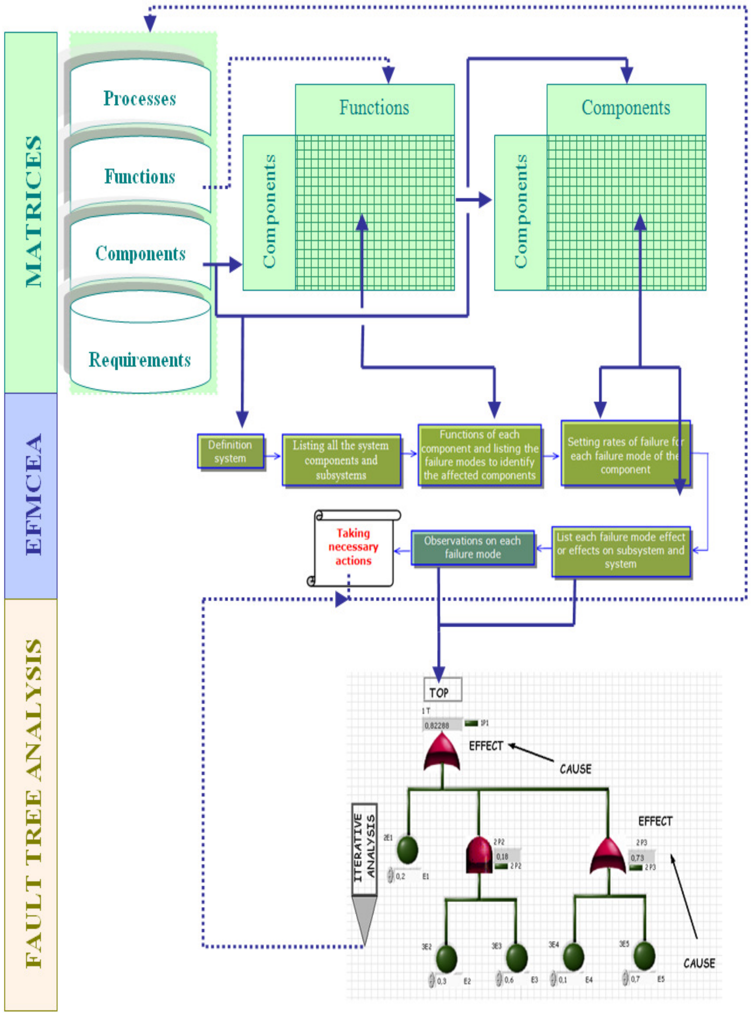


Figure 2. The combination method for prediction durability and safety for fuel cell design

In this paper performance in design fuel cell system is based on conceptual reliability cycle that included few integrated engineering methods like Fault Modes, Effect and Critically Analysis (FMEA) [26], Fault Tree Analysis (FTA) and Fuzzy logic (figure 1).

2.1 The PEM fuel cell model

Fuel cell model consists of five principles of conservation: mass, momentum, species, charge, and thermal energy. These transport equations are then coupled with electrochemical processes through source terms to describe reaction kinetics and electro-osmotic drag in the polymer electrolyte.
That system fuel cell is a complex system including the interactions of mechanical, chemical, and electrochemical subsystems.

2.1.1 Modelling of the PEMFC system

The mathematical models of PEMFC can be found in the literature like in [5–8]. Basically, a model of PEMFC consists of an electro-chemical and thermo-dynamical parts. Correa et al. [5] introduce an electro-chemical model of a PEMFC to validate this model; the polarization curve obtained with this model is compared to the polarization curve of the manufacturing data sheet.

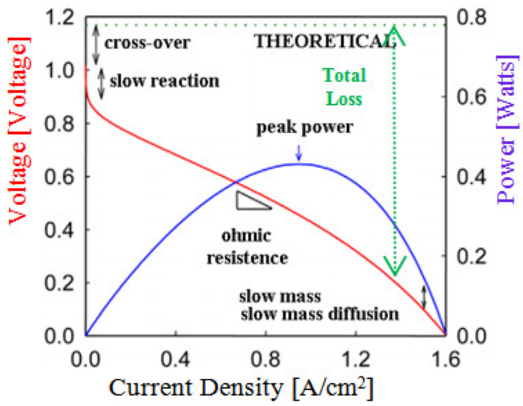


Figure 3. Typical Polarization Curve (for PEM Fuel Cell)

In Ref. [9], the thermo-dynamical part of the model and the effects of different types of faults are included.
The key performance measure of a fuel cell is the voltage output as a function of electrical current density drawn, or the polarization curve, Fig. 2 [21, 22].
Current (rate of reaction) (i) depends on:

- Electrode area, A;
- Concentration of reactant, c;
- Temperature, T;
- The kinetic parameters i_0 and α;
- Overpotential, η;
  and is given by Butler-Volmer equation:

$$i = i_0\left(e^{\frac{(1-\alpha)nF}{RT}\eta} - e^{\frac{-\alpha nF}{RT}\eta}\right) \tag{1}$$

The FC model is based on the calculation of voltage, temperature, and humidity, according to the equations considered in Ref. [5,7]. The voltage V_{FC} of a single cell can be defined as the result of the following expression [5]:

$$V_{FC}=E_{Nernst}-V_{act}-V_{ohmic}-V_{con} \tag{2}$$

E_{Nernst} is the thermodynamic potential of the cell representing its reversible voltage:

$$E_{Nersnst} = 1.229 - 0.85\times10^{-3}(T-298.15) + 4.31\times10^{-5}T[\ln(P_{H_2}) + \tfrac{1}{2}\ln(P_{O_2})] \tag{3}$$

V_{act} is the voltage drop due to the activation of the anode and the cathode:

$$V_{act} = -[\varepsilon_1 + \varepsilon_2\, T + \varepsilon_3\, T ln(c_{O_2}) + \varepsilon_4\, T ln(I_{FC})] \tag{4}$$

where ε_i $(i = 1 \dots 4)$ are specific coefficients for every type of FC, I_{FC} (A) is electric current, and c_{O_2} (atm) is the oxygen concentration:

$$c_{O_2} = \frac{P_{O_2}}{5{,}08\times10^6\times e^{-\left(\frac{498}{T}\right)}} \tag{5}$$

Where P_{H_2} and P_{O_2} (atm) are the hydrogen and oxygen pressures, respectively and T (K) is the operating temperature.
V_{ohmic} is the ohmic voltage drop associated with the conduction of protons through the solid electrolyte, and of electrons through the internal electronic resistance:

$$V_{ohmic} = I_{FC}(R_M+R_C) \tag{6}$$

where R_C(Ω) is the contact resistance to electron flow and R_M (Ω) is the resistance to proton transfer through the membrane:

$$R_M = \frac{\rho_M l}{A}$$

$$\rho_M = \frac{181{,}6[1+0{,}03\left(\frac{I_{FC}}{A}\right)+0{,}062\left(\frac{T}{303}\right)^2\left(\frac{I_{FC}}{A}\right)^{2{,}5}]}{[\epsilon-0{,}634-3\left(\frac{I_{FC}}{A}\right)\exp[4{,}18\left(\frac{(T-303)}{T}\right)]]} \tag{7}$$

where ρ_M(Ωcm) is the specific resistivity of membrane, l (cm) the thickness of membrane, A (cm^2) the active area of the membrane, and ϵ is a coefficient for every type of membrane.
V_{con} represents the voltage drop resulting from the mass transportation effects, which affects the concentration of the reacting gases:

$$V_{con} = -Bln(1 - \frac{J}{J_{max}}) \tag{8}$$

where B(V) is a constant depending on the type of FC, J_{max} the maximum electric current density, and J is the electric current density produced by the cell (A/cm^2). In general, $J=J_{out}+J_n$ where J_{out} is the real electrical output current density and J_n is the fuel crossover and internal loss current.
Current density of the cell is defined by the expression:

$$J = \frac{I_{FC}}{A} \tag{9}$$

Considering a stack composed by several FCs, and as initial approximation, the output stack voltage can be considered as:

$$V_{Stack} = nV_{FC},$$

where n is the number of cells composing the stack and V_{FC} is the cell output voltage for each operating condition.
However, constructive characteristics of the stack such as flow distribution and heat transfer should be taken [10–14].
The instantaneous electrical power supplied by the cell to the load can be determined by the equation:

$$P_{FC} = I_{FC} \times V_{FC} \tag{10}$$

where P_{FC} is the output power (Watts).
The FC efficiency can be determined by the equation [18]:

$$\eta = \mu_f \times \frac{V_{FC}}{1,46} \tag{11}$$

where μ_f is the fuel utilization coefficient, generally in the range of 95%, and 1,48V corresponds to the maximum voltage that can be obtained using the higher heating value for the hydrogen enthalpy.
The variation of temperature in the FC is obtained with the following differential equation [3]:

$$\frac{dT}{dt} = \frac{\Delta Q}{MC_s} \tag{12}$$

where M(kg) is the whole stack mass, C_s (JK^{-1}kg^{-1}) the average specific heat coefficient of the stack, and ΔQ is the rate of heat variation (i.e. the difference between the rate of heat generated by the cell operation and the rate of heat removed).
Four types of heat can be removed: heat by the reaction air flowing inside the stack (Q_{rem1}), by the refrigeration system (Q_{rem2}), by water evaporation (Q_{rem3}), and by heat exchanged with the surroundings (Q_{rem4}).
Water forms at the cathode, and because the membrane electrolyte is very thin, water would diffuse from the cathode to the anode during the operation of the cell. The water formation would keep the electrolyte hydrated. This level of hydration is measured through the relative humidity of the output air.
To calculate the relative humidity of the output air, the balance of water is establishes: output=input + internal generation, or in terms of the partial pressure of water: $P_{W_{out}} = P_{W_{in}} + P_{W_{gen}}$ and, also $HR_{out}P_{sat\_out} = P_{W_{out}}$, then the HR_{out} is:

$$HR_{out} = \frac{P_{W_{in}}+P_{W_{gen}}}{P_{sat\_out}} \tag{13}$$

where $P_{W_{in}}$ is the partial pressure of the water in the inlet air, $P_{W_{gen}}$ the partial pressure of the water generated by the chemical reaction, and P_{sat_out} is the saturated vapor pressure in the output air.
The P_{sat} is calculated from the following equation:

$$P_{sat} = T^a exp\frac{\left(\frac{b}{T}\right)+c}{10} \tag{14}$$

If T > 273.15 K, then a=−4.9283, b=−6763.28, and c=54.22;
The rate of water production (kg s^{-1}) is calculated from the next equation [3]:

$$m_{H_2O} = 9,34 \times 10^{-8} I_{FC} \times n \tag{15}$$

For normal operation of the FC, proper temperature and humidity should be maintained. If the HR_{out} is much less than 100%, then the membrane dries out and the conductivity decreases. On the

other hand, a HR_{out} greater than 100% produces accumulation of liquid water on the electrodes, which become flooded and block the pores, making gas diffusion difficult.
The result of these two conditions is a fairly narrow range of normal operating conditions. In abnormal conditions such as flooding or drying, parameters (such as R_C and ϵ) that are normally constant (Table 1) start to vary.
The parameters of the FC model for normal conditions [6] are presented in Table 1. These parameters are estimated by an optimization process.

Table 1. Parameters for the FCS

Parameter	Value
n	4
A[cm^2]	60
l[μm]	25
P_{O_2}(atm)	0,2
P_{H_2}(atm)	1,5
ε_1	– 0,948
ε_2	$0{,}00286+0{,}0002\ln A+(4{,}3\times10^{-5})\ln c_{H_2}$
ε_2	$7{,}22\times10^{-5}$
ε_4	$-1{,}06153\times10^{-4}$
ϵ	23
$R_C(\Omega)$	0,003
B (V)	0,015
J_n (A/cm^2)	0,022
J_{max} (A/cm^2)	0.672

III. PROBLEM SOLUTION

Based on modelling of the PEMFC system (FCS), especially on the calculation of voltage (2), temperature (12), and humidity, according to the equations (13), the rate of water production (15), are prepared component matrices of functions according to the method of Fig. 1, then is achieved FMECA in LabVIEW software as in Fig. 4 and Fig.5.

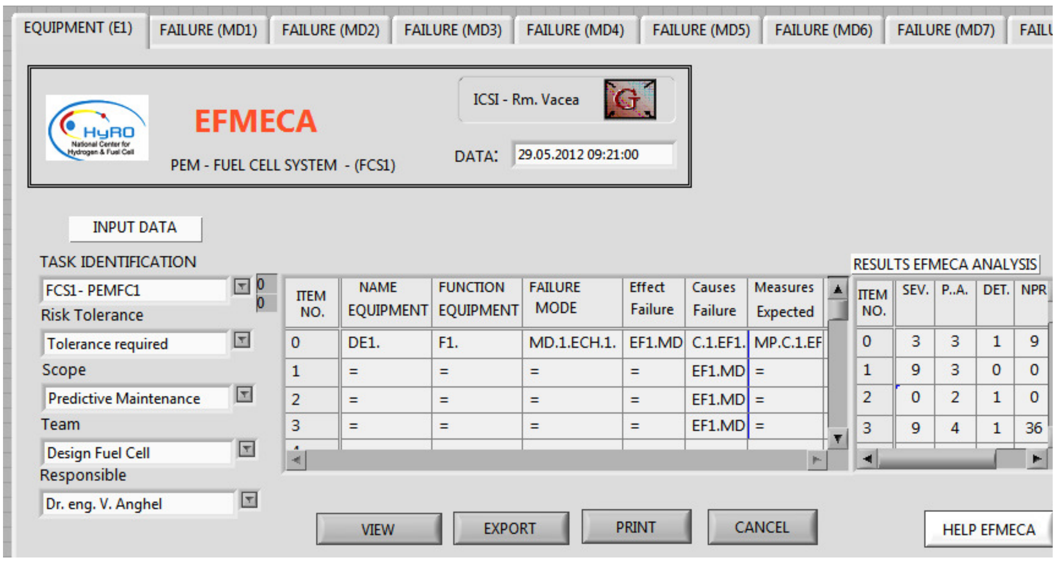


Figure 4. The front panel application of modeling and simulation EFMECA for FCS

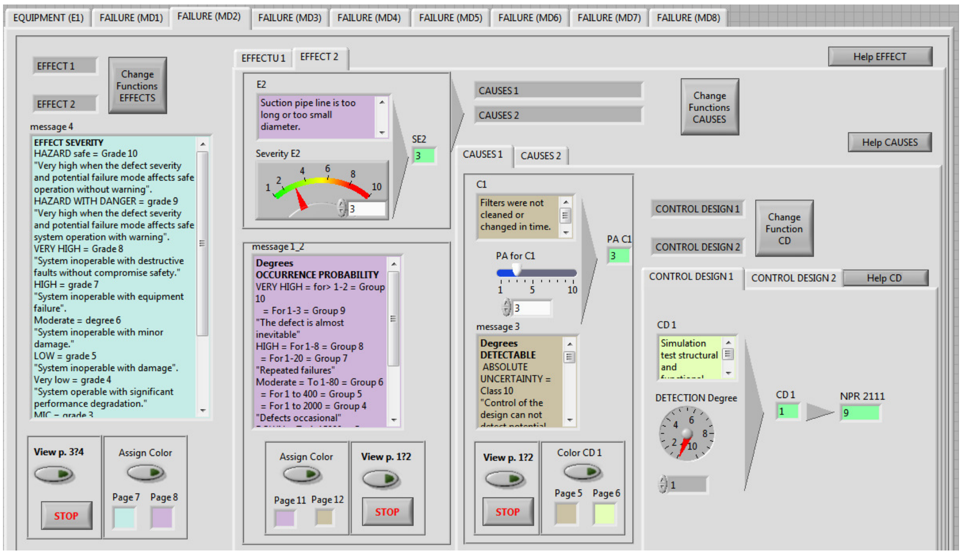


Figure 5. Failure mode effects and critical analysis with LabView for FCS

To solve the optimization problem in abnormal conditions, the Simulated Annealing (SA) optimization algorithm was used [19], [20]. For example SA algorithm at FCM is:
Initialization (Initial parameter set - H_2 pressure)
Calculation of the output voltage (V_S),
LOOP
New_State
Calculation of the new output voltage (VS),
IF $\Delta(Current\ V_S\ - New\ V_s) \le 0$
THEN
Current_State = New_State
ELSE
IF $Exp(\frac{Current\ V_S - New\ V_S}{\mathrm{H_2\ pressure}}) > Random(0,1)$
THEN
--Accept
Current_State = New_State
ELSE
--Reject
Current_State = New_State
Decrease the H2 pressure
EXIT When STOP_CRITERION
END LOOP

and, similar for electric current (I_{FC}), relative humidity (HR_{out}), and for Air pressure, too. The FCM was tested in different fault conditions.
Table 2 illustrates the possible evolution of different physical parameter establish in terms of fuzzy logic variable.
A fuzzy logic relates the outputs to the inputs using a list of if–then statements called rules (see Table 3 as an example of rules).

Table 2. Setting parameters for fuzzy analysis as input for FTA

P(atm)	Low()	Normal()	High()
Vs (V)	Low()	Normal()	High()
I_{FC} (A)	Low()	Normal()	High()
HR_{out}(%)	Low()	Normal()	High()

For the implementation of the EFMCEA, fuzzy logic has been used. Previous research [15] and [16] already indicated that fuzzy logic is very suitable for FCS control. It is a good method for realizing an optimal trade-off between the efficiencies of all components of the FCS. It is also very robust, because it is tolerant to imprecise measurements and to component variability. The general strategy described in the previous section has been implemented using a Takagi–Sugeno fuzzy logic [24].
A fuzzy logic relates the outputs to the inputs using a list of if–then statements called rules (see Table 3 as an example of rules).

Table 3. Rule base on the fuzzy logic for top event at FTA for EFMCEA strategy

1	*If* P_{H_2} *is low then* V_S *is very low*
2	*If* P_{H_2} *is low then* I_{FC} *is very low*
3	*If* P_{H_2} *is low then* HR_{out} *is low*
4	*If* P_{air} *is low then* V_S *is low*
5	*If* P_{air} *is low then* I_{FC} *is low*
6	*If* P_{air} *is low then* HR_{out} *is normal*
7	*If T is low then* HR_{out} *is high*
8	*If T is normal then* HR_{out} *is normal*
9	*If T is high then* HR_{out} *is low*
...	*If ...is ... then ... is ....*

The fuzzy input variables in the rules are P_{H_2}, P_{air}, T and the single fuzzy output variable is reliability. Each variable has a range, sometimes referred to as its universe of discourse. The IF part of a rule is its antecedent and the THEN part is its consequent. Fuzzy input variables always appear in rule antecedents. A rule consequent refers to one or more fuzzy output variables. The words like “low,“ “normal,” and “high” are adjectives describing the fuzzy variables. It is defined that adjective by specifying a function that gives the degree to which each value of the variable is described by the adjective. These functions are called membership functions because they represent degrees of membership in fuzzy sets. The if-part of the rules refers to adjectives that describe regions (fuzzy sets) of the input variable. A particular input value belongs to these regions to a certain degree, represented by the degree of membership. The effects of different types of faults can be simulated adapting a FCM, avoiding damage to the component or vary from normal parameters of operation and improving the generating time of fault records. In the FC model is introduced more types of faults in PEMFC like: *faults in the air fan*, *faults in the refrigeration system, growth of the fuel crossover, faults in hydrogen pressure, Catalyst Degradation, Dynamic Response Characteristics and Influencing Failure Factors, Low Relative Humidity, Feed Starvation, Contamination Impacts and Mechanisms in Low-Temperature PEM FCs, etc*.
When a fault occurs, an interconnected dependence among the variables is established; in general, all the variables perform some kind of changes. That hinders the diagnosis of the fault cause. To qualify and quantify the dependence among the variables, a FTA is constructed to conduct the fault diagnosis. The variables considered are the following:

F_c = fault by fuel crossover
F_{ab} = fault in the air blower
F_{rs} = fault in the cooling system
F_{Hp} = fault by low H_2 pressure
v_{af} = volume of air flow
q_{gen} = generated heat
λ = stoichiometric air relationship
HR = output relative humidity
d_m = drying of membrane
f_d = flooding of electrodes
o_v = overload
V_s = voltage stack
I_{FC} = electrical current of the FC
T = temperature
P_{ol} = difference between real output power and required load
P_{H2}= H2 pressure

To design FCS that work correctly it is need to understand and correct how it can go wrong.
FTA identifies models and evaluates the unique interrelationship of events leading to:

- Failure
- Understand events / states
- Unintended events / states

Method FTA (Fault Tree Analysis) is well known worldwide as an important tool for assessing the safety and reliability in design, development and operating system considered. For over 40 years, FTA is used in aviation, nuclear and mechanical engineering to implementation failure behaviour of systems in a visual diagram based on the root cause that top event. Fault Tree proves to be concise, visual representation and the most common use cases for:

- Identify safety-critical components;
- Verified the product;
- Certification of product reliability;
- Risk assessment;
- Investigating accidents / incidents;
- The causes and consequences;
- Identification of common cause faults.

FTA is a deductive method of analysis begins with a general conclusion and then infers specific causes leading to this conclusion. FTA is based on a logical set of rules and symbols, that probability theory and Boolean algebra. This method uses an approach "top-down" logic model to generate qualitative and quantitative assessments of system reliability. Undesired event in the system considered is represented as "top event". Lower level for each branch of the tree of failure is "basic events". These events may represent the failure of hardware, software and human for which probability of failure is determined based on historical data.

3.1 Fuzzy Fault Tree method

Fuzzy fault tree methodology [17], according to the following steps:

- plot the graph of tree failure model, using the logic symbol and logic gates;
- modulation tree failure and qualitative analysis;
- preparing the list of connection tree failure;
- Boolean transformation matrix to determine sets of cuts.

The approach consists of the following:

- basic event data fuzzification, trapezoidal membership functions;
- estimating the probability of top event (defuzzification);
- sensitivity analysis (defuzzification);
- the importance of cut sets;
- fuzzy share index based events.

FFT method adopts fuzzy numbers to describe the probability of random events. Number fuzzy failure probability p is noted that:

$$p_f = (m - a, m, m + b) \tag{16}$$

where: m is equalizer value of the fuzzy number; a, b - left and right of the distribution parameter fuzzy number. If the probability of the event i is a fuzzy number p_{fi},

$$p_{f_i} = \prod_{i=1}^{n}(m_i - a_i, m_i, m_i + b_i) \tag{17}$$

the fuzzy operator gate "AND" is:

$$P_{AND} = \prod_{i=1}^{n} p_{f_i} = (p_{AND}^a, p_{AND}, p_{AND}^b) \tag{18}$$

$$p_{AND}^a = \prod_{i=1}^{n}(m_i - a_i) \tag{19}$$

$$p_{AND} = \prod_{i=1}^{n} m_i \tag{20}$$

$$p_{AND}^b = \prod_{i=1}^{n}(m_i + b_i) \tag{21}$$

The fuzzy operator of gate "OR" is:

$$P_{OR} = 1 - \prod_{i=1}^{n}(1 - p_{f_i}) = (p_{OR}^a, p_{OR}, p_{OR}^b) \tag{22}$$

$$p_{OR}^a = \prod_{i=1}^{n}[1 - (m_i - a_i)] \tag{23}$$

$$p_{OR} = 1 - \prod_{i=1}^{n}(1 - m_i) \tag{24}$$

$$p_{OR}^{b} = 1 - \prod_{i=1}^{n}[1 - (m_i + b_i)] \quad (25)$$

3.2 Application Fuzzy Fault Tree for Fuel Cell

A fault tree is a logic diagram that displays the interrelationships between a potential critical event in a system and the reasons for this event [23] and is the graphical representation of the fault tree analysis. A typical fault tree is consists of the top event, the basic events, and the logic gates. Fig. 6, illustrates a fault tree structure with typical components. The top event represents an undesirable state of the system, the basic events represent the state of the systems components, and the logic gates describe the relationship between the basic events and the top event. In classic fault tree analysis the AND logic gate denotes that the output is in a failure state, if all the inputs are in failure state. The OR logic gate denotes that the output is in failure state, if at least one of the inputs is in failure state. An intermediate event represents an intermediate state of the system that is related directly or indirectly to the top event with a logic gate.
Fuzzy fault tree analysis [25] extents classic fault tree analysis, which is based on the assumption that there are sound and clear success and failure states in a system and that failures occurs at random. Fuzzy fault tree analysis can be implemented when:

- There are no clear boundaries between failure and success states of the system, or when it is not clear if the performance of the system fulfils its specifications.
- The probability of system failure cannot be calculated precisely due to the lack of sufficient data and due to the existence of “noise” in the data set.
- There is subjective evaluation of the reliability, which is made with natural language expressions.

In the context of fuzzy fault tree analysis, given a fault tree structure it is possible to calculate the subjective reliability of the corresponding system, given information about the reliability of the system components in linguistic terms. These terms are translated into fuzzy sets. The fuzzy sets express the subjective possibility of failure (i.e. the subjective unreliability) of the system. This is done by mapping each linguistic value to a range of subjective failure possibilities through a fuzzy set membership function. The subjective failure possibility is defined on the unit interval [0,1]. Thus, If Pos(E1), Pos(E2), … Pos(En) are the failure possibilities of the basic events E1, E2, … En respectively, and the corresponding components of the system are independent, then the output possibilities of the AND – OR gates can be calculated with the following formulas [24]:
$Pos_{AND} = Pos(E_1) \otimes Pos(E_2) \otimes \ldots \otimes Pos(E_n)$
$Pos_{OR} = 1 \ominus (1 \ominus Pos(E_1)) \otimes (1 \ominus Pos(E_2)) \otimes \ldots . \otimes (1 \ominus Pos(E_n))$
Where: Pos_{AND}, Pos_{OR} are the possibilities of the output events of the AND and OR logic gates respectively and the symbols $\otimes$ and $\ominus$ denote the fuzzy subtraction and multiplication. Through the outputs of the AND - OR gates it is possible to determine the subjective possibility of the top event following a bottom–up calculation approach. In some cases the independence of the top events might not be possible. In general, for mobile and stationary applications, hydrogen is supplied by a high-pressure bottle, which is reduced by a pressure regulator. In normal conditions, the hydrogen pressure is assumed to be constant (generally between 1 and 3 atm). A lower pressure negatively affects the performance of the FC. The reduction of H_2 pressure decreases the E_{Nernst}, increases the V_{act}, and has a corresponding effect on V_{FC}. In this section, the effects of one types of faults on the FC operation were explained simply and directly. However, when a fault occurs, an interconnected dependence among the variables is established; in general, all the variables perform some kind of changes. That hinders the diagnosis of the fault cause. To qualify and quantify the dependence among the variables, a FFTA is constructed to conduct the fault diagnosis.

3.2.1 Faults to hydrogen pressure of FCS.

Probability of failure on the circuit will determine the fault tree analysis and fuzzy, which involves calculating the probability of basic events, operators that use fuzzy logic gates. It is assumed that each elementary event leading independent event (Fig. 6), will be as follows: P = defect hydrogen buffer vessel + Defect in hydrogen Failure to pipelines+ supply FCS. For example, buffer vessel manufacturing defect hydrogen = p1 + Event1 + p2 = Event2 + Event3 + Event1 + Event4 + Event5 + event6. Fuzzy number is used to describe the likelihood of various events, so it follows:

$$P_1 = X_2 + X_3 \quad (26)$$

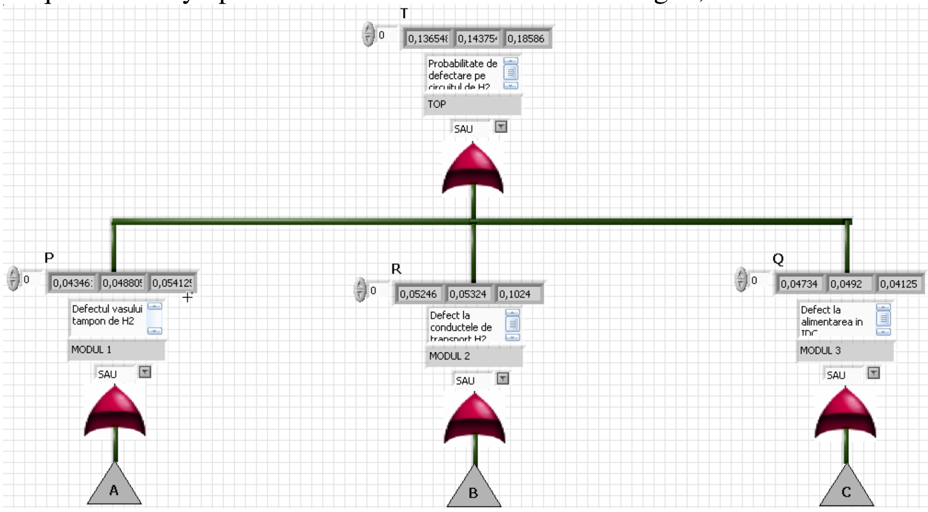
$$P_2 = X_4 + X_5 + X_6 \tag{27}$$

$$P = P_1 + X_1 + P_2 = X_2 + X_3 + X_1 + X_4 + X_5 + X_6 \tag{28}$$

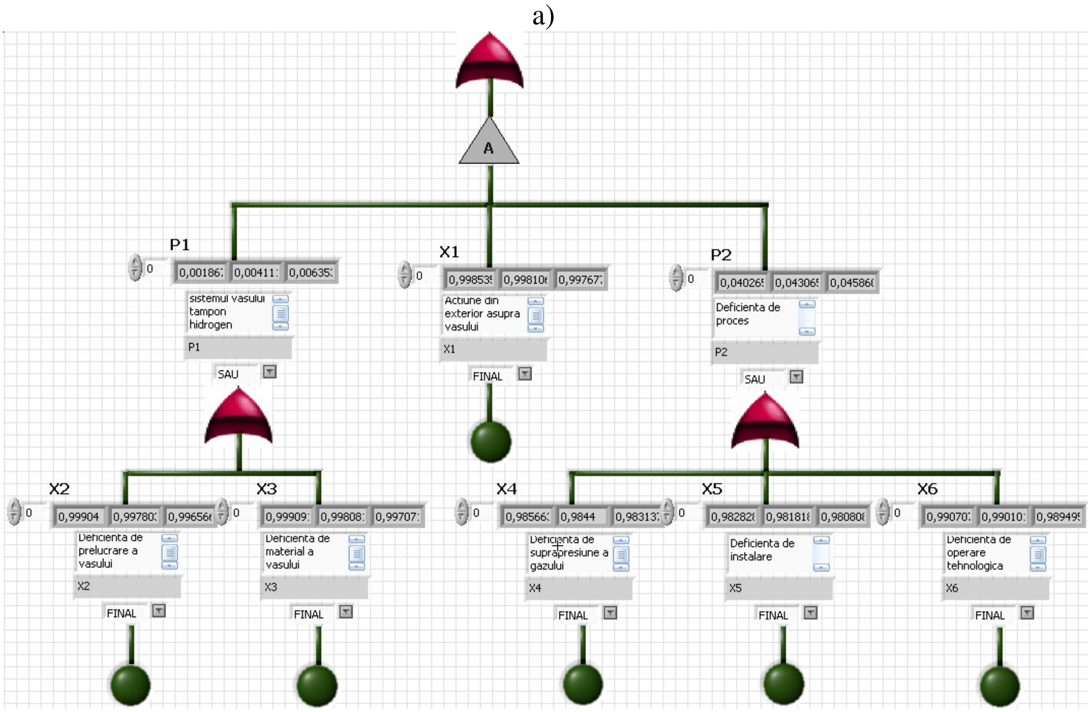
Note that set of cuts of fault tree analysis determines the change in equivalent Boolean algebraic equation as follows:

$$P = \sum_{i=1}^{6} X_i \tag{29}$$

So, the set of cuts directly affect reliability. When defining the top event of the vessel defect hydrogen buffer T, the probabilities mi of all events fi have are presented in Fig. 7.
According to equation fuzzy operator and intermediate results of Fig. 7, can be obtained:



a)



b)

P1: Leaking hydrogen system buffer vessel; P2: Failure to process 1; R: Inactivation of hydrogen pipelines; Q: Failure to process 2; X1: Action outside the vessel; X2: Deficiency manufacture vessel; X3: Material failure of the vessel; X4: Gas pressure deficiency; X5: Installation failure; X6: Deficiency of operating technological.

Figure 6. Graph tree failure inactive transmission and distribution of hydrogen in FCS

$$\bar{P}_1 = \bar{X}_2 + \bar{X}_3 = (0{,}00186; 0{,}00411; 0{,}00635) \tag{30}$$

$$\bar{P}_2 = \bar{X}_4 + \bar{X}_5 + \bar{X}_6 = (0{,}04026; 0{,}0430; 0{,}04586) \tag{31}$$

If the confidence is $c = 0{,}6$, then:

$$\bar{P}_1^c = \bar{X}_2^c + \bar{X}_3^c = (0{,}04194; 0{,}04306; 0{,}04418) \tag{32}$$

$$\bar{P}_2^c = \bar{X}_4^c + \bar{X}_3^c = (0{,}04194; 0{,}04306; 0{,}04418) \quad (33)$$

$$\bar{P}_2^c = \bar{X}_4^c + \bar{X}_5^c + \bar{X}_6^c = (0{,}00321; 0{,}04111; 0{,}005) \quad (34)$$

Thus, the probability of chance of fuzzy defect leading to buffer hydrogen vessel is given by:

$$\bar{P} = \bar{P}_1 + \bar{X}_1 + \bar{P}_2 = (0{,}04346; 0{,}04880; 0{,}05412) \quad (35)$$

and is fuzzy number.

Calculation of different levels of trust determines confidence intervals of the top event. Similarly calculate the probability of defect at all other possible causes of failure in FCS. Probability of top event circuit related to the installation FCS is (0.10806, 0.13056, 0.19036).

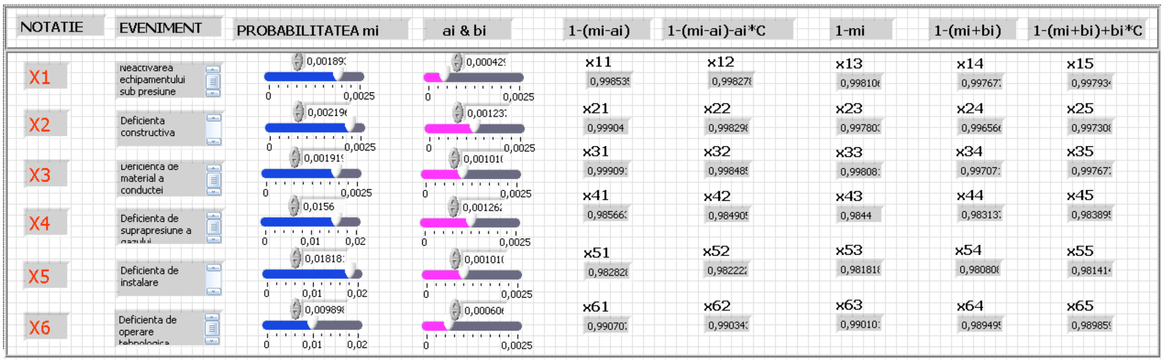


Figure 7. Simulation data and validation of the example of fig. 6, b.

FFTA method is good for qualitative and quantitative reliability analysis of FCS, because data on the dynamic system faults are dependent on a variable degree of uncertainty, so this method better reflects the evolution operability FCS than the classical FTA. This method not only reflects fuzzy probability of the event, it allows to determine the existence of errors allowed. Meanwhile, it allows operators to connect with FCS engineering, that a few tests to compare data with operating experience of FCS. In this method can be consider the human factor, which is very important for safe operation of the FCS.

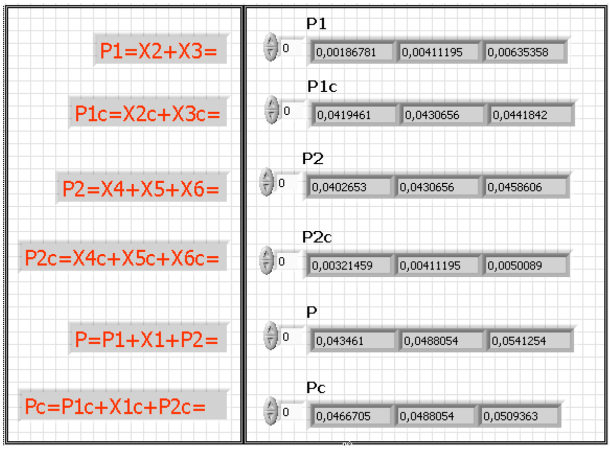


Figure 8. Fuzzy values for probabilities of FFTA.

IV. Result and Discussion

Based on preliminary design or/and historical date in functionary is computed matrices of criticality with LabVIEW software for obtaining PEMFC failure criticality, continued with EFMECA like in figure 5 then are determined the prediction failures based on fuzification variable and FFTA method or the top event for undesirable damage cause. So is possibility achievement of Mean Time Between Failures (MTBF), Failure In Time (FIT) is another way of reporting MTBF or Mean Time To Repair (MTTR) or Mean Time To Failure (MTTF) or life cycle prediction, even from design phase for PEMFC system. In finally is obtained probabilities value for life time of PEMFC and similarly in the integrated systems PEMFC for application in automotive industries.

V. CONCLUSION

The paper proposes the integration some methods, which significantly increases performance of PEMFC based on LabVIEW software. In order to improve fuel cell performances, it is essential to understand technological parametric effects on fuel cell operation. Fuel cell models require physical parameters that manufactures usually do not provide. Therefore, a few methods like EFMCEA, fuzzy logic, must be developed in order to obtain reliable simulations results. Following this objective, a new predictive diagnosis method for accurate model of Proton Exchange Membrane Fuel Cell (PEMFC) systems is presented in this paper. The method adopted in order to determine the optimum set of technological parameters in FFTA algorithm, which proves to be well adapted to satisfy this goal of a fast convergence to establish right values for the cell parameters. The optimized results show a good agreement between experimental and simulated date. As a result, the model allows at getting the all parameters within analytical formulation of any fuel cell. In consequence, fuel cell performance and failure predictive diagnosis are well described as they are carried out through a methodology EFMECA for PEMFC model. It can be used as a block in the construction of simulators or generation systems using fuel cells with good dynamic response. Validated prediction models analysis with EFMECA and FFTA could make it possible to predict the lifetime of PEM fuel cells in automotive applications as a function of known operating conditions and the constitutive behaviour of the PEMFC.

REFERENCES

[1] Payne, T. *Fuel Cells Durability & Performance.* US Brookline: The Knowledge Press Inc. 2009.

[2] M. Fowler, R.F. Mann, J.C. Amphlett, B.A. Peppley, P.R. Roberge, in: W. Vielstich, H.A. Gasteiger, A. Lamm (Eds.), *Handbook of Fuel Cells: Fundamentals, Technology and Applications*, vol. 3, John Wiley & Sons Ltd., 2003, pp. 663–677.

[3] S.J.C. Cleghorn, D.K. Mayfield, D.A. Moore, J.C. Moore, G. Rusch, T.W. Sherman, N.T. Sisofo, U. Beuscher, J. Power Sources 158 (2006) 446–454.

[4] S. Srinivasan, B. Kirby, in: S. Srinivasan (Ed.), *Fuel Cells: From Fundamentals to Applications,* Springer Science/Business Media, 2006, pp. 542–552.

[5] J. Larminie, A. Dicks, *Fuel Cell Systems Explained*, John Wiley & Sons Ltd., 2003.

[6] J.M. Correa, F.A. Farret, L.N. Canha, M.G. Simoes, *An electrochemical-based fuel cell model suitable for electrical engineering automation approach* IEEE Trans. Ind. Electron. *51* (5) (2004) 1103–1112.

[7] N. Fouquet, C. Doulet, C. Nouillant, G. Dauphin-Tanguy, B. Ould Bouamama, *J. Power Sources 159* (2) (2006) 905–913.

[8] K. Promislow, B. Wetton, J. *Power Sources 150* (4) (2005) 129–135.

[9] L.A.M. Riascos, M.G. Simoes, P.E. Miyagi, J. *Power Sources 165* (1) (2007) 267–278.

[10] P.A.C. Chang, J. St-Pierre, J. Stumper, B. Wetton, J. *Power Sources 162* (1) (2006) 340–355.

[11] S.A. Freunberger, M. Santis, I.A. Schneider, A. Wokaun, F.N. B¨uchi, *J. Electrochem. Soc. 153* (3) (2006) A396–A405.

[12] S.A. Freunberger, A. Wokaun, F.N. B¨uchi, *J. Electrochem. Soc. 153* (3) (2006) A909–A913.

[13] G.-S. Kim, J. St-Pierre, K. Promislow, B. Wetton, *J. Power Sources 152* (1) (2005) 210–217.

[14] M. Santis, S.A. Freunberger, M. Papra, A. Wokaun, F.N. B¨uchi, *J. Power Sources 161* (2) (2006) 1076–1083.

[15] Jalil, N., & Kheir, N. (1998). *Energy management studies for a new generation of vehicles* (Milestone No. 6, fuzzy logic for the parallel hybrid). Technical Report, Department of Electrical and Systems (1998).

[16] Kono, H., *Fuzzy control for hybrid electric vehicles.* Master's thesis, Department of Electrical Engineering, The Ohio State University, Columbus, OH, USA (1998).

[17] Sanjay Kumar Tyagi, D. Pandey and Reena Tyagi (2010). *Fuzzy set theoretic approach to fault tree analysis* International Journal of Engineering, Science and Technology Vol. 2, No. 5, 2010, pp. 276-283.

[18] J.M. Corrêa, F.A. Farret, V. A. Popov and M. G. Simões, *Sensitivity analysis of the modeling parameters used in simulation of proton exchange membrane fuel cells*, IEEE Trans. on Energy Conversion, vol. 20, pp. 211 – 218, Mar. 2005.

[19] Stephane Moins, *Implementation of a simulated annealing algorithm for Matlab*, Report n° LITH-ISY-3339-2002

[20] W. Friede, S. Raël, and B. Davat, *Mathematical model and characterization of the transient behavior of a PEM fuel cell*, IEEE Trans. Power Electronics, vol. 19, nº5, pp. 1234-1241Sept. 2004.

[21] Crow DR. *Principles and applications of electrochemistry*. 3rd ed. London: Chapman & Hall; 1988.

[22] Bockris JO'M, Srinivasan S. *Fuel cells: Their electrochemistry*. New York City: McGraw-Hill; 1969.

[23] Hoyland, A., Rausand, M., 1994. *Systems Reliability Theory Models and Statistical Methods*, John Willey & Sons, New York.
[24] Ross ,T. J., 2004. *Fuzzy logic with applications*, 2nd Edition, John Willey and Sons.
[25] Yuhua, D., Datao, Y., 2005. *Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis.* Journal of Loss Prevention in the Process Industries 18 (2)
[26] Aravinth .P , Subramanian .S.P, Sri Vishnu .G, Vignesh .P, 2012. *Process failure mode and effect analysis on tig welding process - a criticality study.* International Journal of Advances in Engineering & Technology, ©IJAET

Short Biography

Vasile ANGHEL, Doctor Engineer and Senior Researcher in Hydrogen Energy and Fuel Cell, Senior CAD/CAM Designer Occupational field is renewable energy / hydrogen and fuel cells / reliability science / integrated engineering / Design for X at Department - National Center for Hydrogen and Fuel Cell-NCHFC (Laboratory Design Fuel Cell), in National Research and Development Institute for Cryogenics and Isotopic Technologies - ICSI Rm.Valcea, Romania.