GIANTLEAP

DELIVERABLE D2.1

PUBLIC

Model-based prognostic algorithm for PEM fuel cells system

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FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

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Abstract: This deliverable gives an overview of the model-based prognostic approach developed by UFC for the PEM fuel cells system (stack and BoP). The system model is developed under the Energetic Macroscopic Representation, EMR formalism, integrating the ageing behavior of the BoP key elements, such as the stack and the air supply unit. The different algorithms are presented and the remaining useful life (RUL) is defined for each key element. The strategies and hypothesis adopted for the RUL evaluation are discussed. The developed algorithms will be tuned with the experimental data provided by BEG and EK and software implementation will be presented in the next deliverable (D2.2).

Revision History

Date	Description	Author
December 05, 2017	First version of the deliverable Revised Version of the deliverable	Raffaele Petrone, UFC Nadia Steiner/Daniel Hissel, UFC

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1 Introduction

Mobility sector can be assumed as one of the main greenhouse gases producers, as the continuous increase on road transports shows an impact in CO_2 emissions and global warming. In this scenario, GIANTLEAP aims to contribute to the creation of free-emission public transport systems, integrating both battery (B) and fuel cells (FCs) technologies in city-bus. To this purpose, a fuel cell range extender is developed to support electric buses batteries on load demand.

As a matter of fact the transport applications loads are quite stressing in terms of repeated start and stop conditions and high load dynamics (sudden acceleration and load variations) [1-5]. Repeated for a long time, these conditions affect not only the FC system balance of plant (BoP) operations, but also the FC durability. To avoid BoP and hybridization issues and fuel cell ageing, new control, diagnosis and prognostics approaches to enhance the FC system durability are then required. In the framework of the GIANTLEAP project, not only the stack durability is evaluated but also the BoP components', with the common objective to provide useful information to the control unit for system management and maintenance activities. To these purposes, a model-based approach is considered for prognostic.

This Deliverable presents the structure of model-based prognostic approach developed by UFC for the PEM fuel cells system (stack and BoP). The system model uses the Energetic Macroscopic Representation (EMR) formalism, integrating the ageing behavior of the BoP key elements, such as the PEMFC stack and the air supply unit. The different algorithms are presented and the remaining useful life (RUL) is defined for each key element. The strategies and hypothesis adopted for the RUL evaluation are discussed. The defined algorithms will be tuned with the experimental data provided by BEG and EK; software implementation will be presented in the next deliverable (D2.2). The common background required to model the real system operations and the related hypothesis to obtain the system RUL are presented in section 2. Section 3 is dedicated to the developed algorithms presentation.

2 Background for model-based prognostic approach

Providing a proper system management is the primary target for real applications: prognostic and health management (PHM) techniques [6-13] are crucial to schedule mitigation and recovery actions, and to enhance the PEMFC system durability during operation. The relevant background to develop a model-based prognostic approach in the framework of the GIANTLEAP project is reported in the following.

2.1 Real system configuration & available data

In the framework of GIANTLEAP project a trailer-mounted fuel cells range extender for battery buses is developed. The main objective is to obtain a modular device that can be easily mounted on electrical buses to extend the bus range of about 300Km.

The system concept is reported on Figure 1, where it is possible to distinguish two main modules: the electrical bus powertrain and the trailer. The information related to the model inputs and outputs, as well as the load demand (profile) that the FC system have to provide to the electrical bus is obtained at the interface between the two modules. The FC system to model is circled in black. The different sub-systems, as well as the FC stacks, the hydrogen line, the air line and the cooling system, are also drafted. For a better understanding of the different sub-systems interactions for model development, a plan is proposed in Figure 2.

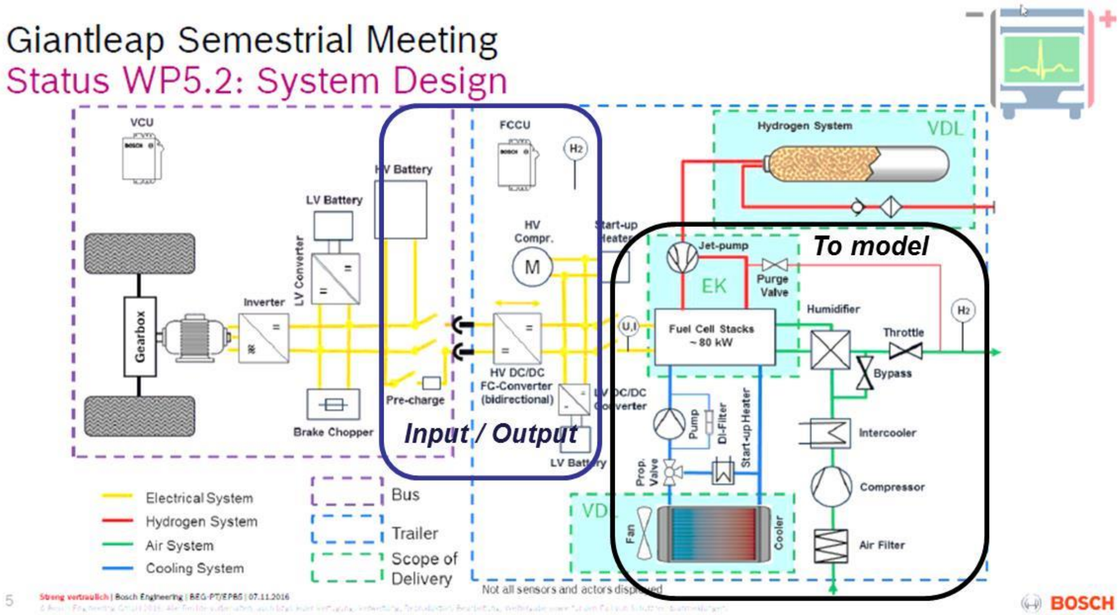

Figure 1: FC range extender, concept proposed by BEG.

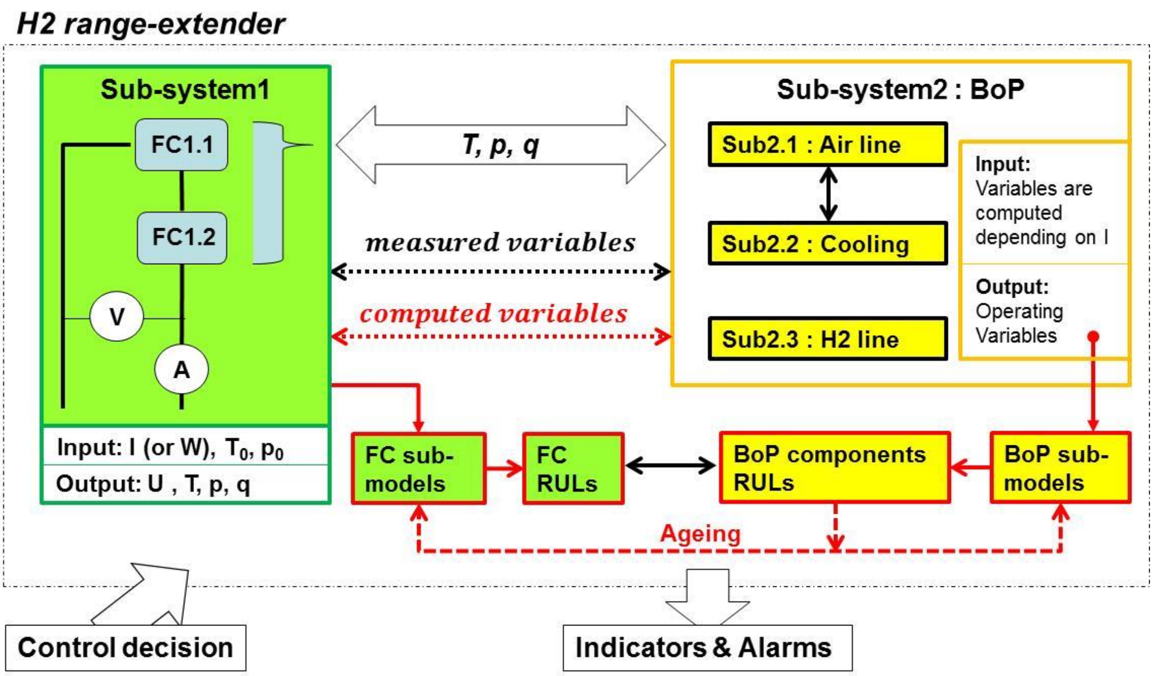

Figure 2: FC range extender scheme for prognostic aimed model development.

The first sub-system to model is the two PEMFC stacks electrically connected in series: reactants inlets are connected in parallel, while the cooling water inlet connections are in series. The second sub-system to model is the BoP components, and particularly the air and hydrogen lines and the cooling system. Starting from the electrical power demand, and depending on the current load profile, the control system will pilot the BoP components' operation to provide the nominal values for FC stacks operation. The same strategy is assumed into the model design. A sub-model is considered for each sub-system and influence of the components ageing in system operations is taken into account; this part will be clarified in section 3. Once the global structure is presented, the background related to different sub-systems is introduced; the available information and the performed hypothesis for model development are finally presented.

Data referring to the PEMFC stacks are provided by EK. Data are confidential and can be summed-up as following:

- PEMFC stacks characteristic and operations.
- Long-term tests results under load variation (7000h): load profile and polarization curves.

Historical data were provided. Currently new measurements acquired on the improved stack developed within the GIANTLEAP project are under delivery. These data are used to tune the electrochemical model of the stack and identify the related ageing functions' parameters; more details on the related algorithm are presented in the next section (paragraph 3.2). The assumed hypotheses of the PEMFC stacks model are:

1. The load profile used for long-term tests is closed to the actual vehicle dynamics load profile.
2. Transitory conditions are not taken into account in a model aimed to prognostic, considering the time variable expressed in hours; faster dynamics are considered in the diagnostic algorithms.
3. To evaluate the polarization curve at the time (t*), a static model is used.
4. Ageing functions describe the model parameters' variations with time (expressed in hours).
5. The polarization curves variations with time are obtained through the ageing functions.

Hypothesis 1 is the strongest. To address this point, the ageing functions are updated following regular scheduled intervals for the on-board application, in order to fit as closely as possible the actual operation and to avoid any problem due to unexpected conditions. The updating is based on on-board identification of the ageing functions' parameters. Therefore, the mathematical laws of the ageing functions are obtained off-line (based on historical data), while their parameters can change on-board and online, depending on actual system ageing trend (refer to Alg. 0 in Figure 9).

Data related to the BoP are provided by BEG; these data are confidential. However, the generic plan for the air line, the cooling system and the hydrogen line sub-models are proposed in Figure 3, 4 & 5, respectively. The available data are summed-up in the following:

- BoP components characteristics & operations.
- BoP tests for key-components ageing:
    - Air compressor tests are scheduled and under development.
    - Historical data for hydrogen jet-pump: data are currently under delivery, to check if predictable ageing can be observed.

The major hypotheses for BoP modelling are summed-up in the following:

1. The control unit will force the BoP operations to attain the target values for FC operations.
2. For the same FC operation set-up, the BoP components operations and/or performance (depending on what is possible to observe) will change with ageing.
3. The FC operation set-up will change with ageing.
4. The resulting variation of the BoP components operations depends both on the FC stack ageing and on the BoP components ageing.
5. The variation of the FC operations set-up induced by ageing must be considered as an additional input of the BoP sub-model.
6. The state of health (SoH) and the RUL of the modelled BoP key-components are evaluated depending on their functioning variation with respect to the FC operations.
7. The selection of the BoP key-components to model is based on:
    a. What is possible to observe.
    b. If the component ageing have a predictable behavior.
8. For the components that show a non-predictable behavior (sudden failures), such as valves, pipelines, throttles, heat exchangers and humidifier, the RUL cannot be evaluated; scheduled maintenance is suggested.
9. The supposed key-components at the beginning of the project are: the air compressor, the water pump, the air fan of the cooling system and the jet-pump.

The hypotheses formulated from point 1 to 8 will be clarified with the algorithms' structure presented into the next section. On the other hand, hypothesis 9 is supposed to change during the project development, if not predictable ageing behavior is observed on available data for the components under examination. As a consequence, an adaptation of the final algorithm configuration can occur depending on point 9.

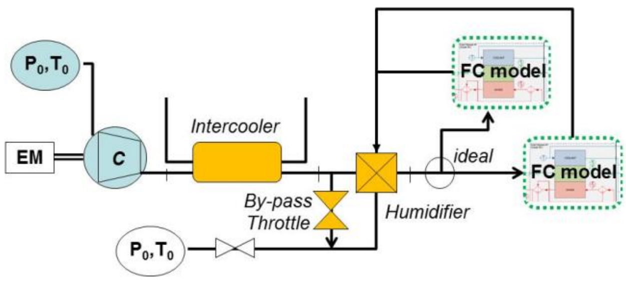

Figure 3: Air line generic schema for modelling.

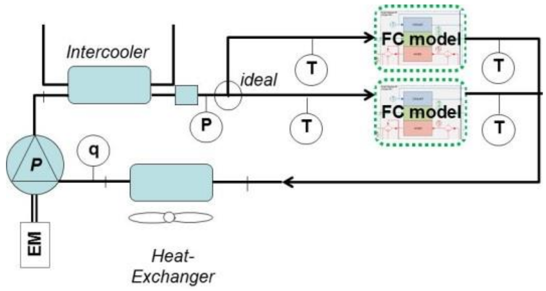

Figure 4: Cooling system generic schema for modelling.

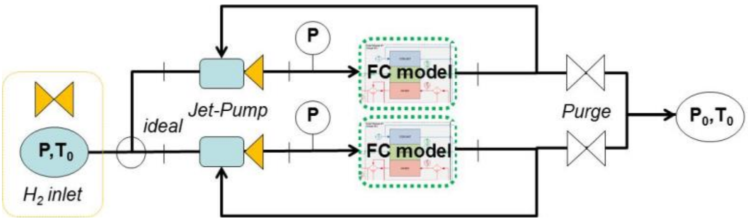

Figure 5: Hydrogen line generic schema for modelling.

2.2 Energetic Macroscopic Representation (EMR)

The first-presented configuration of PEMFC bus range extender developed in GIANTLEAP is a complex multi-domain device that combines, among others, electrical, chemical and thermal aspects. In this context, developing a suited control strategy able to combine both the control unit and the prognostic algorithms could be a relevant solution to allow the system functioning, while ensuring its durability. In fact, the prognostic algorithm will provide to the controller useful information about the system operations in ageing conditions. Depending on the predicted system state-of-health evolution, the controller will then decide to modify the BoP operating conditions with the objective of enhancing the system' lifetime.

To study the impact of the system interactions with the ambient environment and the BoP components operations, a model-based approach is suggested. It is worth noting that the model must be able to simulate the system operations under ageing conditions. Moreover, the model have to run on-board, in parallel to the control unit which requires a good compromise between accuracy and simulation time ratio. For this reason, a multi-physics graphic model, control-oriented formalism is adopted. According to Boulon et al. [14], the Energetic Macroscopic Representation (EMR) "*organizes a complex system in interconnected subsystems and implies to take into account the physical causality principles*". Therefore models equations are opportunely converted in several block (parts) interconnected according to the action and reaction principle. The main advantages of this technique are:

- a clear structured representation of the power flows and interactions between elements is obtained, that can be also used to deduce the system control laws [14,15].

- EMR formalism can be easily developed on Matlab Simulink, and directly implemented on system CPU for on-board applications.

Considering these important points, the EMR formalism is used in GIANTLEAP project to dress the model equations. The main objective is to obtain a global structure able to take into account ageing effects on the different elements and their interactions. This will allow the global system lifetime estimation. The model structure will also underline the ageing impact on control variable indicating useful information for control decisions. An example of the EMR application to model the FC system is given Figure 6. The EMR formalism, based on the work of Boulon et al. [14], is adapted to model both FC and BoP elements interactions. The FC stack model is circled with black dashed line on the right of Fig. 6, while 3 different lines are dedicated to the BoP (on the left of the Figure: 1), for the cooling system (with red dashed line) and 2 for the reactants inlet (with blue dashed line). Regarding the GIANTLEAP prognostic purposes, ageing functions are introduced to model ageing behavior. The obtained voltage trend is then exploited by prognostic techniques to evaluate both the PEMFC and the BOP RULs and to support their maintenance. The global strategy is drafted in Figure 7, where the interactions with the control unit are also underlined.

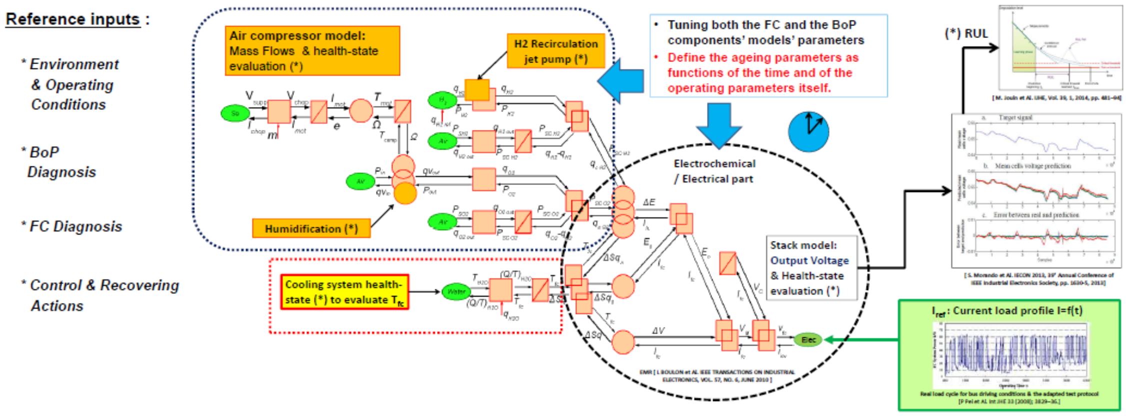

Figure 6: GIANTLEAP EMR structure proposal, presented at the 7th International Conference on Fundamentals & Development of Fuel Cells, 2017 [16].

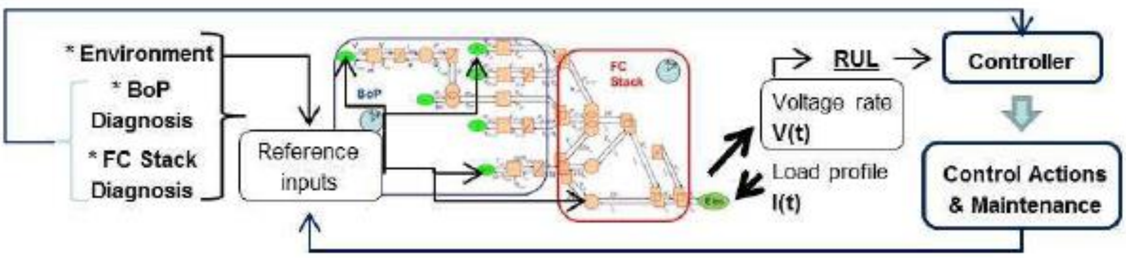

Figure 7: Strategy for EMR-based prognostic, presented at the 7th International Conference on Fundamentals & Development of Fuel Cells, 2017 [16]

It is worth noting that Figure 6 drafts the GIANTLEAP preliminary proposal on EMR prognostic model. This new application aims to design a generic strategy for PEMFC system RUL prediction for transportation applications, supporting system' makers in control decisions and maintenance scheduling. Therefore, depending on the final system configuration, the available data for the model tuning and the on-board measurements, the structure of Figure 6 can be modified. More details on the strategy and on the algorithms' structure development are given in the next section, while the final software is the object of the next deliverable D2.2.

2.3 RUL background

According to Bressel et al. [12] prognostic can be considered as an advanced strategy for system maintenance and reliability improvement. Its definition can be found on the International Organization for Standardization, as: "*the estimation of time to failure and risk for one or more existing and future failure modes*" [17]. Where the word "failure" underlines the system inability to fulfill its function. Therefore, the primary action is to define the degrading failure mode. According to Mohammadian et al. [18], a performance factor must be identified. This factor must be a measurable variable (physical property), that will change with ageing. In other words, to be considered as a performance factor, a predictable variation with ageing must be observed on measurements in time domain. Usually, both expertise knowledge and ageing tests can be adopted to select the performance factor. Once the performance factor defined, depending on the operating conditions, the measured value at the beginning of life (BoL) is assumed as the nominal value (P^N). At the same time, the end of life (EoL) criterion must be defined. Usually, the minimum allowable performance value is considered as the critical performance (P^C) [18]. As a consequence, the system EoL is identified with the P^C value detection. During the system ageing, the state of the performance factor P(t) changes (decreases) from P^N to P^C. In case of multi-failures mode, or to compare different components failures, a unitless "damage" factor [18] is defined as:

$$D(t) = \frac{P^N - P(t)}{P^N - P^C} \qquad \text{(eq. 1)}$$

Resulting: $D(t_{BoL} = 0) = 0$ and $D(t_{EoL}) = 1$

As the consequence, t_{EoL} is the system lifetime for the considered failure mode, while the RUL is evaluate as:

$$RUL = t_{EoL} - t^* \qquad \text{(eq. 2)}$$

Where t* is the time that refers to the current state of health D(t*). Therefore, two main information are required to estimate the remaining useful life of the system [12]:

1. The current system state of health.
2. The system degradation evolution to reach the failure.

Depending on the considered approach (data-driven – a, or model-based – b):

(a) D(t*) is obtained from the on-board measured data, while the degrading evolution trend of the system is extrapolated through interpolation, filters [7], statistical or artificial intelligence methods [9,10].

(b) Both D(t*) and the degrading evolution trend of the system are simulated by the model. It is worth noting that in case of on-board applications, some measurements are performed to verify the model results consistence with the current state of health. In case of deviation of the real degrading trend from the simulated one, an updating of the ageing functions is obtained and real trend recovered.

In case of a global system RUL evaluation, different failure modes have to be analyzed depending on the system key-elements' ageing. According to Mohammadian et al. [18], failures modes can be *dependents* or *independents* if the damage related to a single failure mode affects or not the other ones. In case of independent failure modes, the different RULs can be easily separated. On the contrary, the influence of the key-elements' ageing must be analyzed and considered on global RUL evaluation.

A model-based approach can solve this point. In fact, the different key-elements dependences are usually considered in model structure, if an acceptable *a priori knowledge* is available. This is one of the main reasons for EMR formalism choice in GIANTLEAP project (refer to the previous paragraph): the link between the different sub-components ageing is provided by the model. In this configuration, the damage evolution per each single key-element can be simulated including the components ageing interactions. As a consequence, the global RUL can be defined by observing all the key-elements damage evolutions and by evaluating the critical one. It is worth noting that for the failure definition, each key-element failure will cause the system failure and then, the shorter RUL will be assumed as the most critical one.

3 Model structure & Algorithms

Once the system and methods backgrounds are introduced, the model structure and the related algorithms are presented. First, the global structure and the adopted strategy for control interactions are presented. Subsequently, the key-elements sub-algorithms for simulation are proposed, concluding with the RUL estimation algorithms.

3.1 Strategy & Control interactions

To develop a suited prognostic model-based approach not only the system model but also the different interactions with the control unit, the diagnostic outputs and the on-board measurements must be taken into account. The main flows are drafted in Figure 8. On the left of this Figure is represented the main prognostic and health management (PHM) algorithm (Alg. 1) including both the system components model for simulation and the algorithm for RUL evaluation (Alg. 2). On the opposite side, the communication between the real system, the diagnostic algorithm and the controller is shown. In the middle, a PHM/Control Interface algorithm (Alg. 0) is proposed to manage the different communication flows between the prognostic algorithm and the control unit. A counter, referring to the system clock is also set for time measurements and for synchronization purposes. This kind of configuration allows the PHM updating with control variations, and the possibility to adapt the control strategy with RUL information.

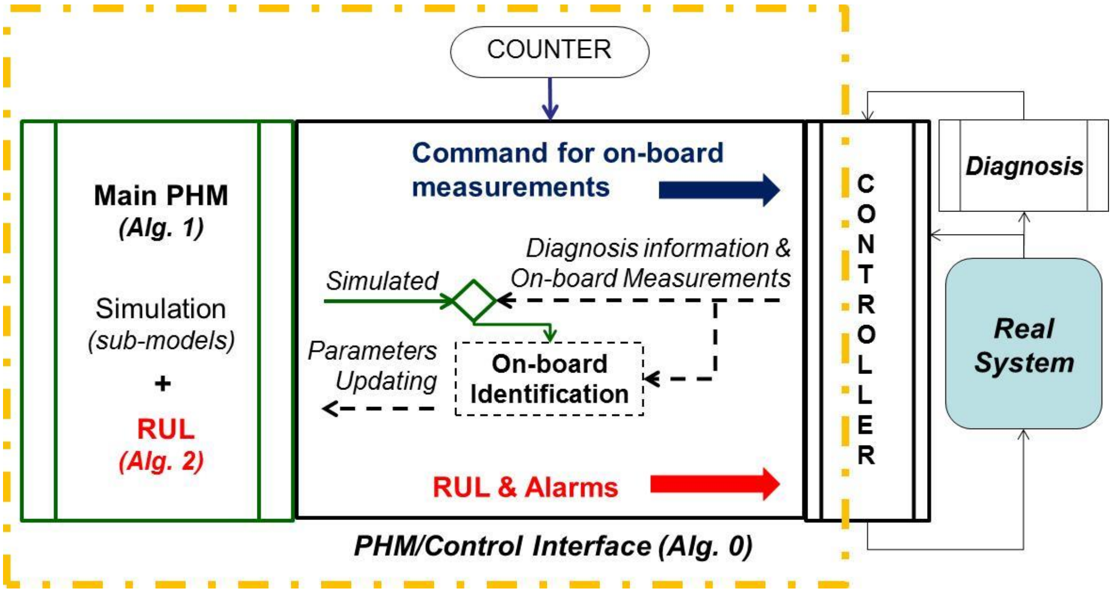

Figure 8: PHM & control interface strategy.

The information and data exchanged in algorithm 0 (refers to Figure 9) are:

1. the counter sends to the controller, the command for scheduled on-board measurements (based on the counter time measurements),
2. the controller sends:
   - Information from *diagnosis* in case of transitory abnormal operations,
   - the on-board measurements generated after:
     - a scheduled counter demand,
     - a change in nominal operation due to diagnosis alert,
     - a change in nominal operation due to RUL alert.
3. the PHM simulator sends the components' simulated state of health to be compared with on-board measurements at time t* (synchronized with counter); if relevant, residuals are observed:
   1. the on-board identification procedure starts,
   2. the simulator ageing functions are updated,
4. the RUL algorithm send to the controller the RUL information and alerts.

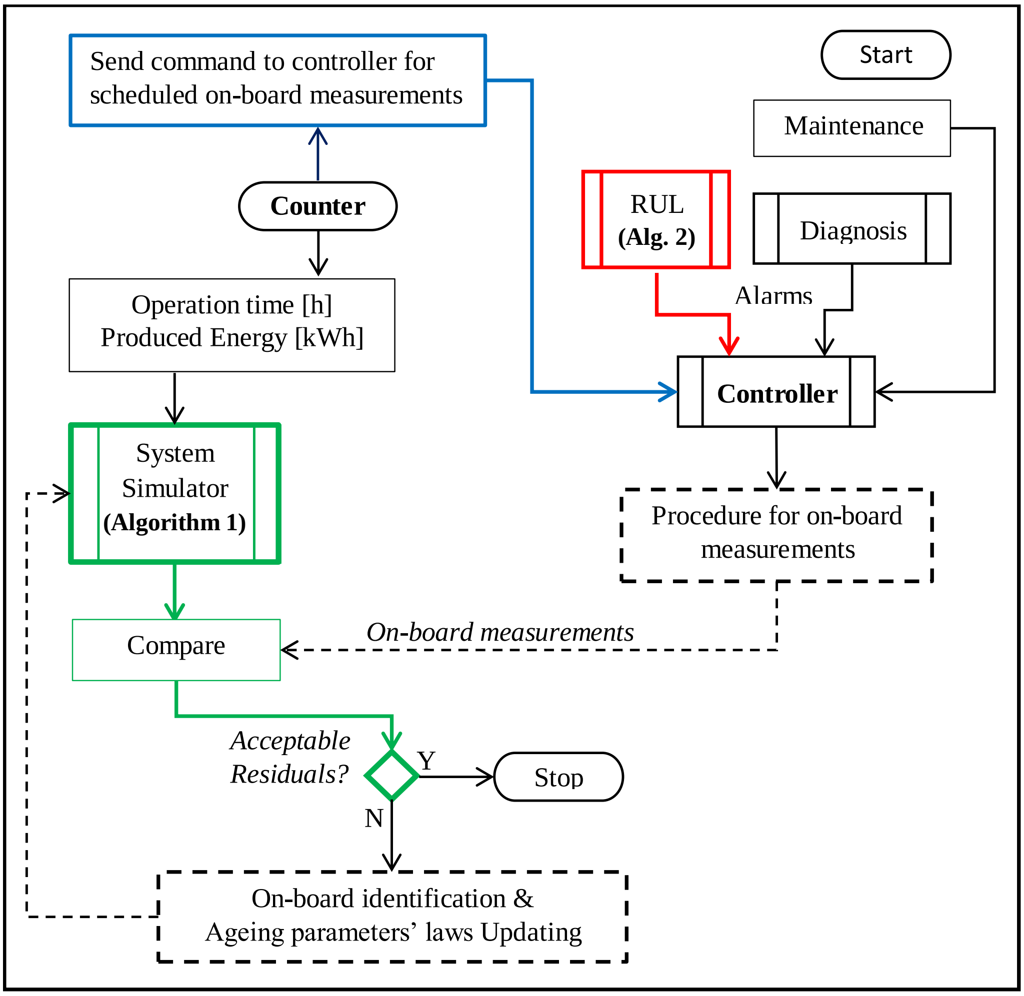

Figure 9: Algorithm 0, PHM/Control Interface.

3.2 Main PHM structure and key-elements simulators

The global structure of the PHM algorithm is proposed in Figure 10. On the top, it is possible to notice the communication with the interface algorithm (Alg. 0). A load analyser is scheduled to extract model input variables in case of a change in system operations (related to control strategies or to diagnosis outputs). At the same time, the ageing functions' parameters updating is also considered. It is worth underlining that the input variables' extraction and the ageing functions in case of normal operations are tuned off-line. However to be consistent with real system operations and stress, the possibility of on-board updating is scheduled. This is a mandatory point for on-board applications to create a suited loop with the controller for the BoP components management. In fact, in case of a new control is applied, the controller will receive the information about the strategy impact on RUL.

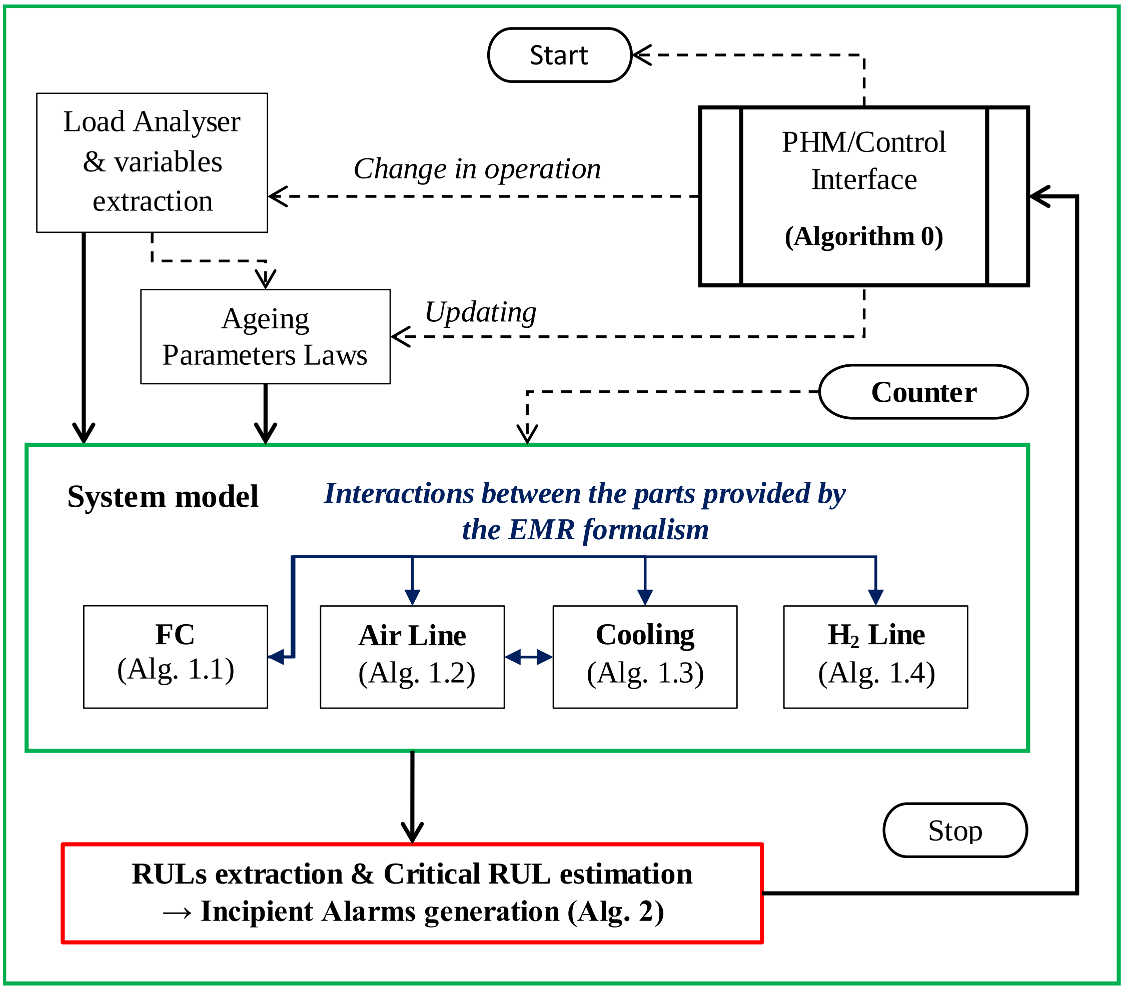

Figure 10: Algorithm 1, Main PHM structure.

Therefore, all the system model inputs are available for simulation. As introduced in the previous section (paragraph 2.2), the EMR formalism is adopted to model the different interactions between model parts (components sub-models). This step aims to obtain both the system state of health at time t* and the degrading performance profile exploited to evaluate the different RULs. As introduced in paragraph 2.3, the link between the different components' operations under aged conditions is performed at this level. Therefore, the different failure-modes dependencies are considered in the simulation results. Finally, algorithm 2 dedicated to RULs extraction and alerts' generation is proposed; this last point will be detailed in paragraph 3.3.

The first sub-system (Alg. 1.1) is the FC stack simulator. The considered model is based on the electrochemical energy conversion equations. Starting from the FC temperature and the inlet reactants properties, the theoretical potential is evaluated. Subsequently, the different voltage drops caused by the activation, ohmic and concentration losses are considered. For each voltage drop, an ageing function is scheduled. These functions are tuned off-line based on ageing tests results (refer to paragraph 2.1). If ageing data are available for different load profiles, the model is able to integrate off-line the related information; if not, the on-board updating is required. Because the model is used for prognostic purposes, the electrical part related to the charge double layer capacitor is not modelled. In other words, transient conditions are neglected, because:

1. the degrading behaviour is analysed in hour and not in seconds,
2. the prognostic is aimed only to the irreversible decay of performance.

The algorithm 1.1 is proposed in Figure 11, while Figure 12 proposes the generic configuration of the EMR formalism.

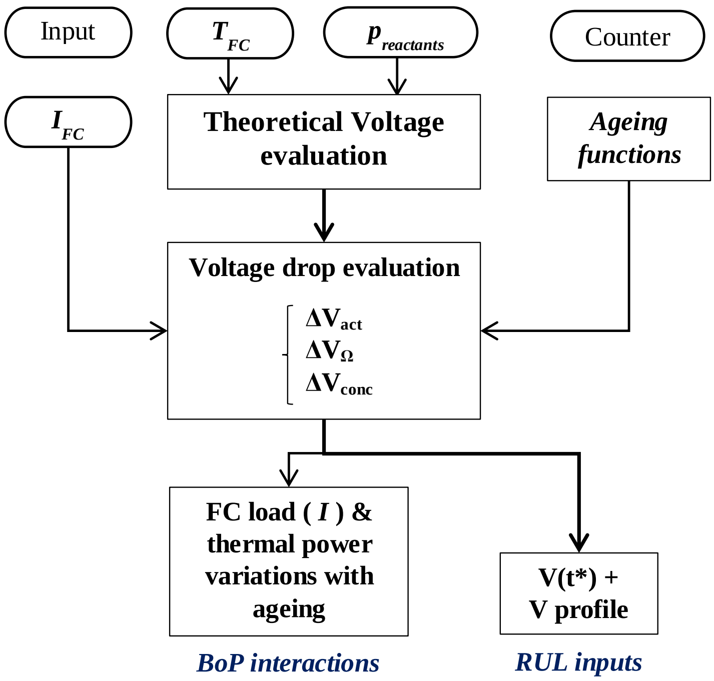

Figure 11: Algorithm 1.1, PEMFC simulator.

The generic EMR configuration is developed based on the structure proposed by Boulon et al. [14]. The original model doesn't involved ageing phenomena. For a better understanding: the green elements are the sources (inputs/outputs), the blue clock is the counter, the squares are the same domain energy conversions, while the circles are used for different domain energy conversion; interactions are represented with full arrows. Model improvement and adaptations can occur depending on the available data.

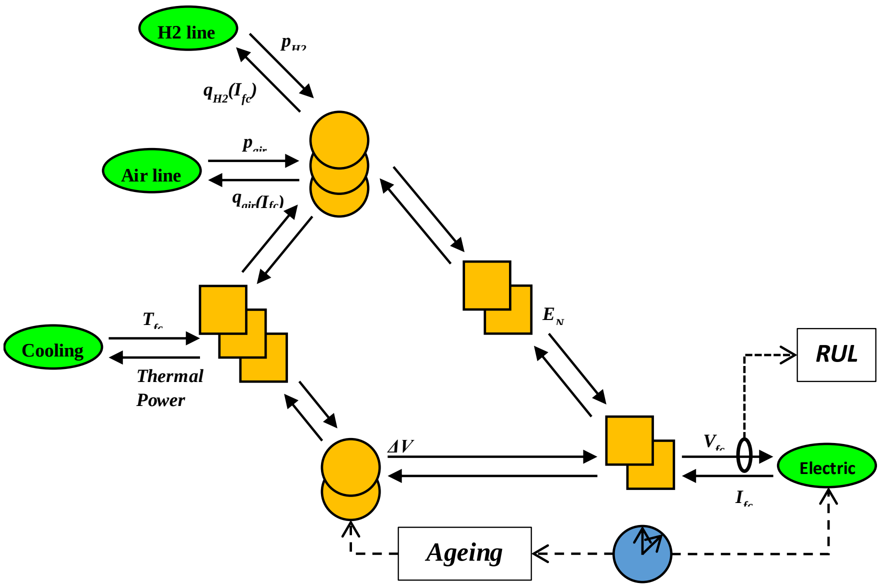

Figure 12: generic EMR model of the PEMFC stack oriented to PHM; the structure is obtained starting from the PEMFC stack model of Boulon et al. [14].

The second subsystem (Alg. 1.2) is the airline simulator, the algorithm of which is proposed in Figure 13. Starting from the information on the current fuel cell load, the required air mass flow and pressure are evaluated. At the same time, the by-pass and the back pressure valves' operations are considered. This part is particularly observable into the EMR structure presented in Figure 14. The same symbols of Figure 12 are adopted. It is possible to notice two processes or informational flows:

1. going from the different sources to the PEMFC to provide the suited input variable values for the PEMFC sub-model (corresponding to the line output of Figure 13).
2. going from the PEMFC to the different sources to evaluate the different input variables per each block starting from the FC current load demand.

Process 2 is used to evaluate the air mass flow, and the different pressures drop information. Therefore, all the main components, such as the humidifier, the intercooler and the air compressor are considered. The link between the cooling system line is done via the intercooler exchanges (refer to Figure 14). According to paragraph 2.1, the key-element of the air line is the compressor. As shown in Figure 13, this element provides the performance input to evaluate the RUL. Referring to the FC load, the compressor will operate to provide the suited air flow. As underlined in Figure 14, starting from the electric motor (EM) the ageing impact is considered. As a consequence, the rotational speed (assumed as performance factor) will change with ageing so as to provide the expected air flow. As introduced in paragraph 2.1, the compressor ageing tests are currently ongoing. The results of these tests are expected to confirm the choice of performance factor and allow the ageing functions tuning. Finally, it is worth noting that a FC ageing will induce a change into the air mass flow demand, resulting in a performance factor variation, that is not due to the compressor ageing. In this case, the process 2 provides to the compressor model the suited information related the stack ageing. As a consequence, the EMR model is able to take into account the stack ageing within the compressor operations' simulation.

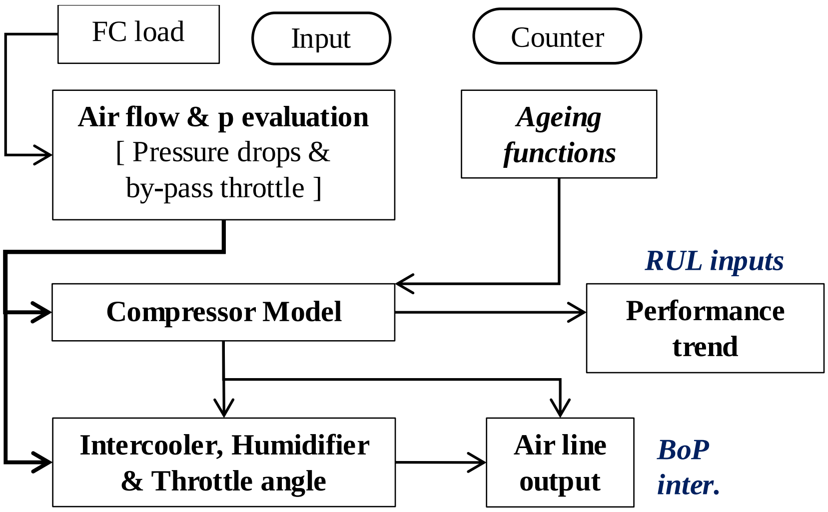

Figure 13: Algorithm 1.2, air line simulator.

The EMR structure presented in Figure 14 is the generic one; depending on the project available data, future model improvements and/or changes (adaptations and simplifications) can be introduced.

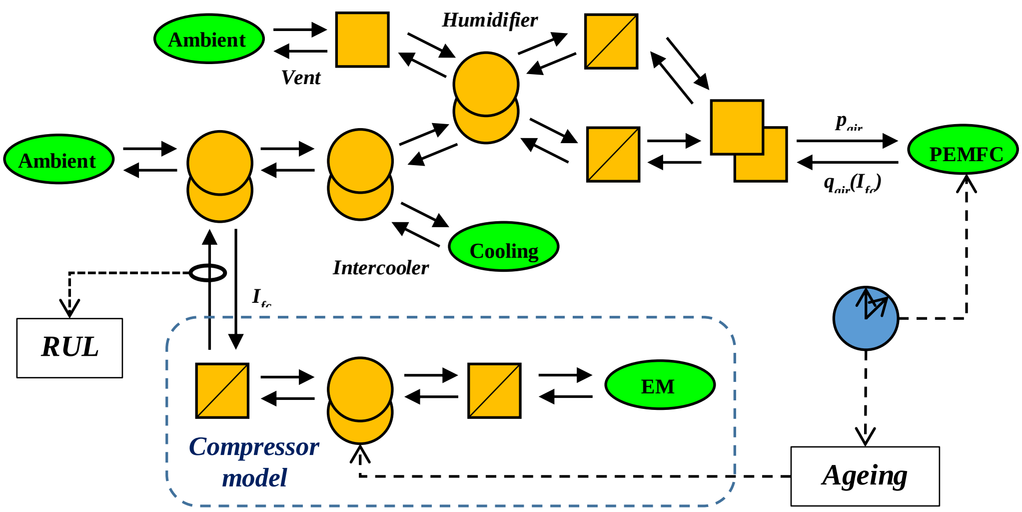

Figure 14: generic EMR model of the air line oriented to PHM.

The third subsystem (Alg. 1.3) is the cooling system simulator, which algorithm is proposed in Figure 15. In analogy with the air line, starting from the current fuel cell load demand, the required water flow and temperatures are evaluated. Two main key-elements are considered: the water pump and the air fan. Per each key element, a related ageing function is set. This part is also observable into the EMR structure presented in Figure 16. As well as for the air line model, the procedure is able to take into account the FC ageing and the induced performance variations on the key-elements' operations.

The impact of the key-elements ageing is also scheduled. However, it is worth to underline that currently not enough data are available to tune the ageing functions related to the water pump and the air fan. Therefore, depending on the future project available data, the generic structure presented in Figure 16 could be modified (simplified). To solve this point due to a possible lack of information, a mitigation strategy in RUL evaluation is proposed in paragraph 3.3.

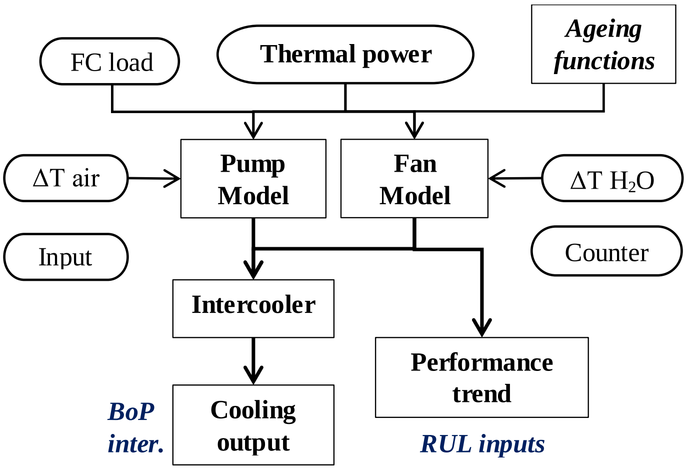

Figure 15: Algorithm 1.3, cooling system simulator.

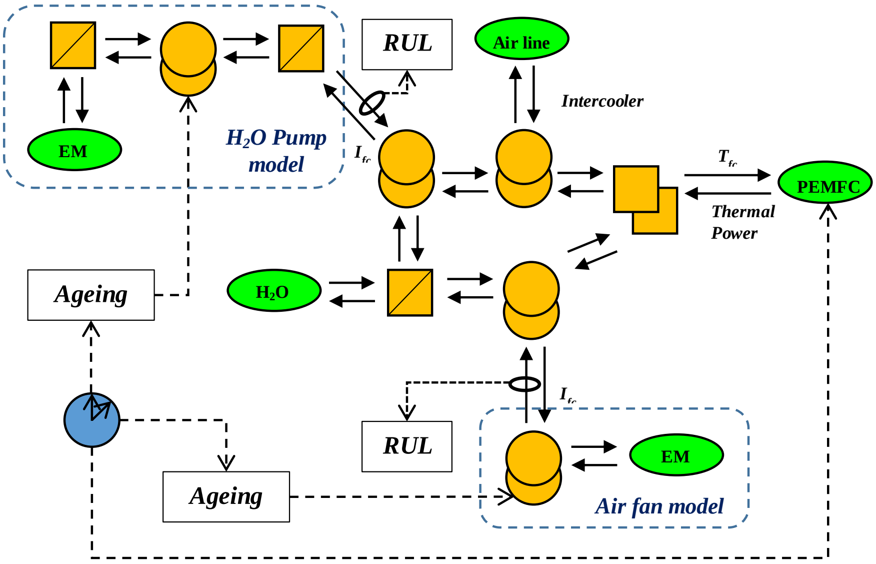

Figure 16: generic EMR model of the cooling system oriented to PHM.

Finally, the forth subsystem (Alg. 1.4) is the hydrogen line simulator, which algorithm is proposed in Figure 17. In analogy with previous BoP sub-models, starting from the current fuel cell load demand, the required hydrogen consumptions and pressures are evaluated. The hydrogen recirculation is modelled with the hypothesis of an adiabatic mixer while the jet-pump is considered as the key-element. The generic algorithm is completed and the generic EMR model is proposed in Figure 18. However, a current lack of information limits the model tuning and particularly the ageing function parameters' identifications. Currently experimental tests results are analysed by BEG. The first results seem not to show a predictable ageing behaviour; other verifications are on-going. Nevertheless, as introduced in paragraph 2.3, if a non-predictable behaviour is observed in any variable, the RUL evaluation cannot be performed. In this case, scheduled maintenance is proposed, while the hydrogen line model will be used to evaluate the impact of the system ageing on the FC hydrogen consumptions. In fact, the EMR models are able to take into account the performance variations due to the FC ageing; so it will be sufficient to identify the hydrogen consumptions as the performance factor to evaluate their variation.

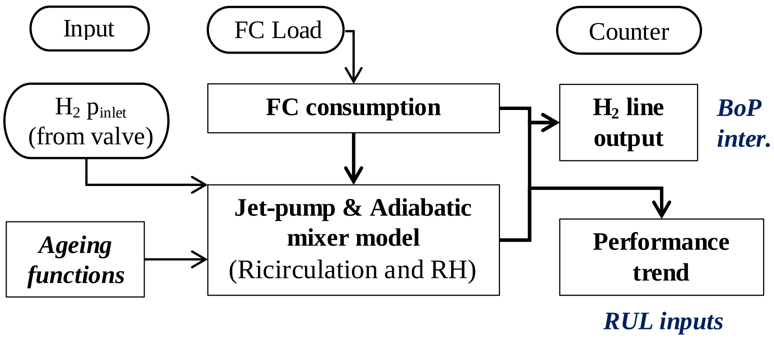

Figure 17: Algorithm 1.4, H_2 line simulator.

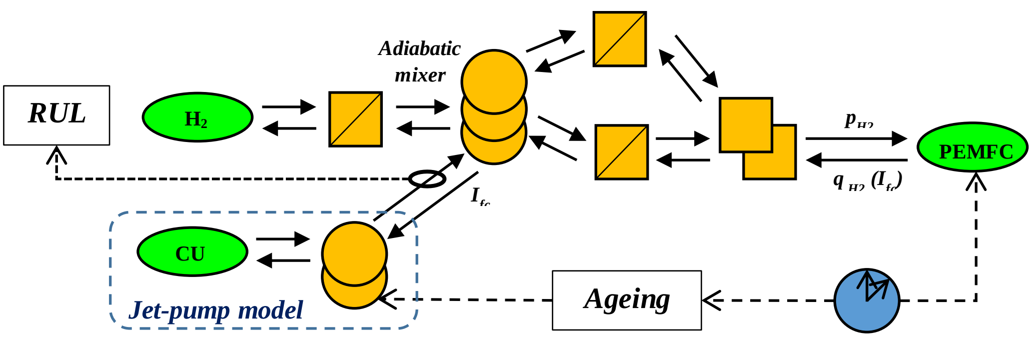

Figure 18: generic EMR model of the hydrogen line oriented to PHM.

3.3 RULs extraction

Once the model structure is presented, the generic algorithm for RUL extraction is proposed. Algorithm 2 is presented in Figure 19. The performance factors that are the circled output variables (arrows) in Figures 12, 14, 16 and 18 are sent from the simulator to the RUL algorithm. In first instance, the PEMFC voltage is observed and the related damage function extracted. In parallel, also the propagation of the error distribution with time is evaluated. Once the damage trend for the FC is obtained, the related RUL is evaluated depending on the critical performance. Subsequently according to paragraph 3.2, a switch is considered, depending if the ageing phenomena can be observed into the BoP components performance behaviour (and available data):

- If a degrading performance is observed, the related RUL is evaluated.
- If not, a new procedure mitigating the lack of information is introduced; more details are given in the following (refer to Figure 23).

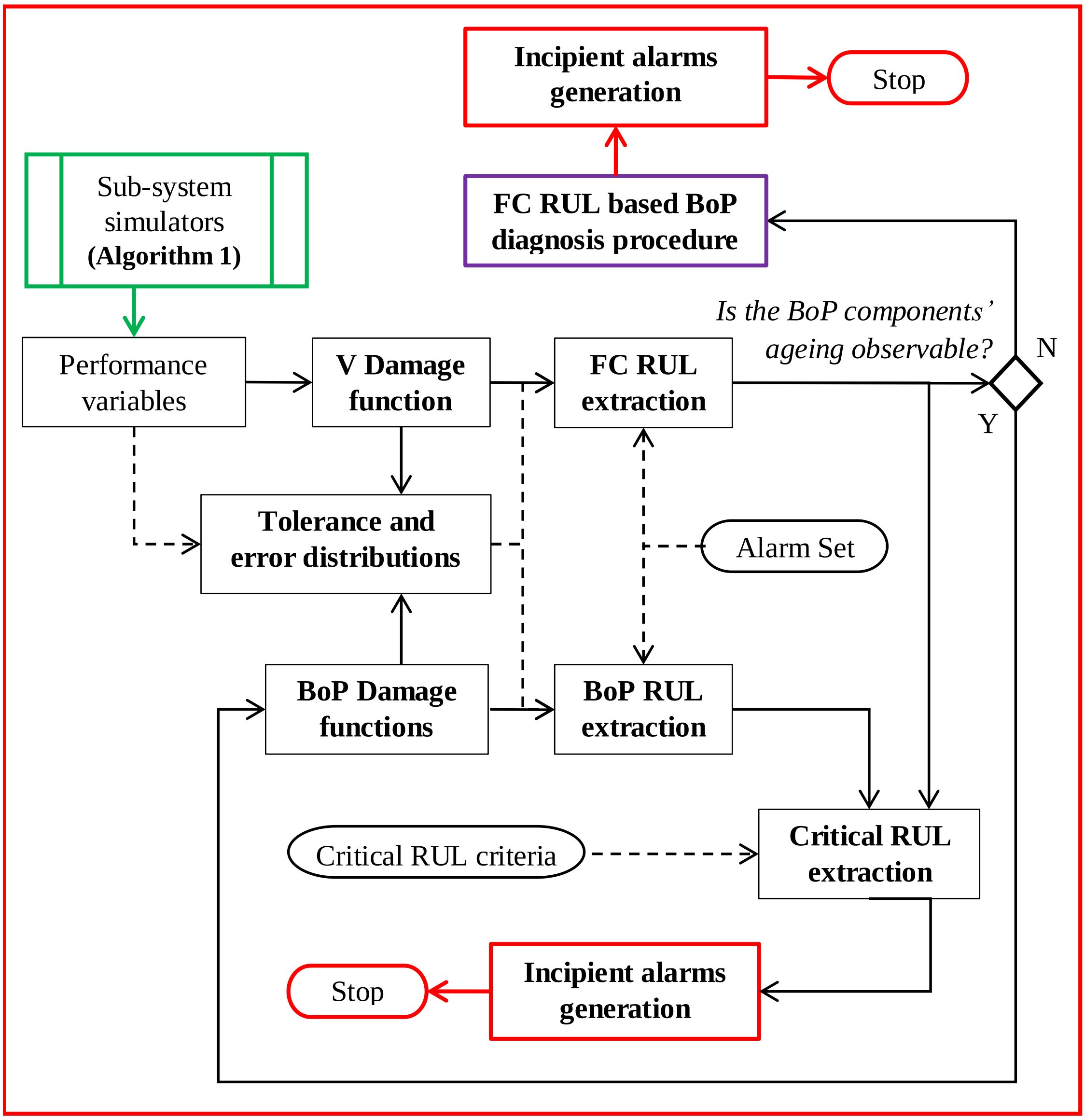

Figure 19: Algorithm 2, RULs extraction & Alarms generation.

Finally, the different RULs are compared and the resulting critical one extracted. Considering that each key-component failure will induce the system failure, the shorter RUL criterion is used. Depending on the RULs' values, an alarm index is evaluated. These index will be sent to the controller as useful information on components state of health. Based on the adopted strategy, the controller will decide about changes in the system management. For a better understanding, the results obtained with the initial available data of the project are presented in the following; here, the mitigation strategy proposed in algorithm 2 will be also clarified.

The long duration test data provided by EK, allowed the stack model tuning and the related ageing functions parameters identification; this step is performed off-line. The results are drafted in Figure 20. On the left of Figure 20, it is possible to observe the polarization curve evolution with ageing. Available data referred to 7000 h of ageing test. Instead, on the right of Figure 20, the 7000h data (points) at OCV, 10, 40, 120 and 220 A conditions are compared with the model simulated trends (full lines) in a range of 40000h. New data related to the improved stacks developed by EK in the framework of the GIANTLEAP project will be available soon. An off-line identification procedure is scheduled for the new stack model and ageing parameters tuning.

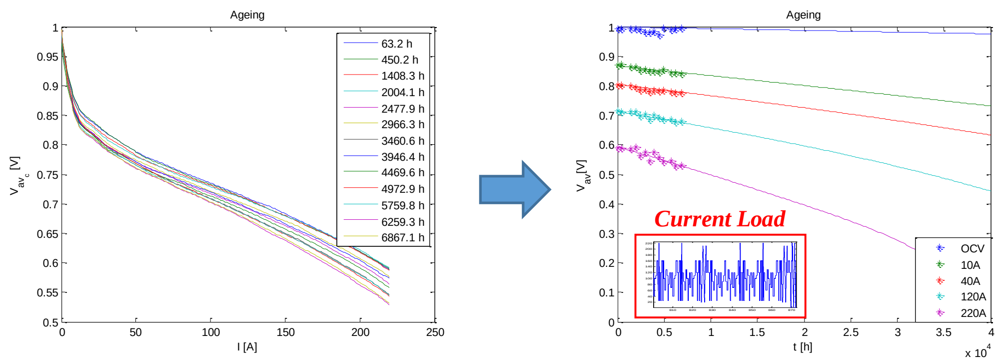

Figure 20: From ageing data (about 7000 h) referred to the polarization curve and the ageing test load profile, to the simulated results (40000 simulated h)

In accordance to the hypothesis introduced in paragraph 2.3, the stack voltage output is considered as a performance factor. On the other hand, the critical performance criteria have to be evaluated depending on manufacturers' specifications. The limitation of 0.6 V per cell was originally indicated by EK, however with the new stack generation, this limitation can be reduced. Another important point to consider is the power demanded by the DC/DC converter for the electrical connection. In fact, the FC range extender have to deliver to the electrical bus a maximum nominal power (P_M); this value was fixed by VDL. Therefore, also if the power demand is converted into a current load profile for the FC system operations, a control loop on the required power is applied. This means that the P_M value must to be taken into account for the RUL extraction. In this context, the model simulates the system operations to fulfill $P_{M.}$ This introduces a first lifetime evaluation that must be verified and corrected depending on the mean cell voltage critical value (0.6 V). This procedure is drafted in Figure 21. Starting from the ageing simulation (1) both power and voltage limitation are considered; for a better understanding, both the power and the polarization curves are reported in diagram 2 and 3, respectively. Consequently, two important results are obtained:

- The lifetime prediction for RUL evaluation (R1).
- The operating conditions variation induced by ageing to obtain P_M (R2).

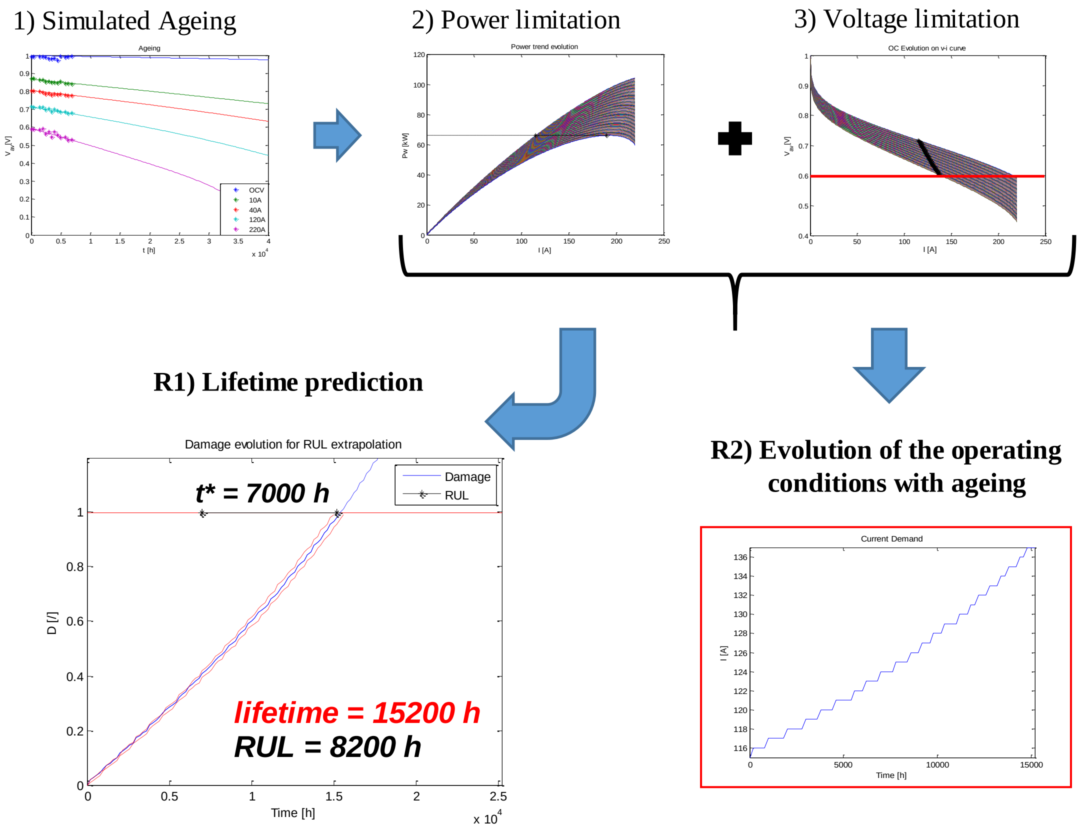

Figure 21: PEMFC RUL and operating conditions evaluation: 1) simulation; 2) power constraint coupled with 3) voltage limitation; R1) RUL extrapolation; R2) change in operating conditions.

R1 results will be exploited for RULs comparison to generate alarms, while the R2 results are used in BoP components' RULs evaluation. In fact, R2 involves the information related to the operating conditions variation with the FC ageing, this point is fundamental for the dependence evaluation of the different failures' modes. In accordance with the hypothesis presented in paragraph 2.1, the control unit will force the BoP operations to fulfil the needs of the PEMFC operations. Therefore, the BoP operations will change with R2.

The simulation results for the air compressor are reported below. Considering the new current profile obtained through R2, the new air mass flow demand is evaluated. As a consequence, the compressor operations changes. Figure 22 shows both the air demand and the compressor operations' evolutions. The rotational speed of the compressor (Ω_c) is assumed as performance factor; its variation related to the PEMFC ageing is also drafted in Figure 22. The same procedure is scheduled for all the BoP components. Considering the BoP key-elements, the rotational speed of the water pump, the rotational speed of the air fan and the hydrogen consumptions are assumed as performance factors for the water pump, the cooling air fan and the jet-pump, respectively. It is worth noting that the BoP ancillaries' critical performance values are defined with the specific component operational limits.

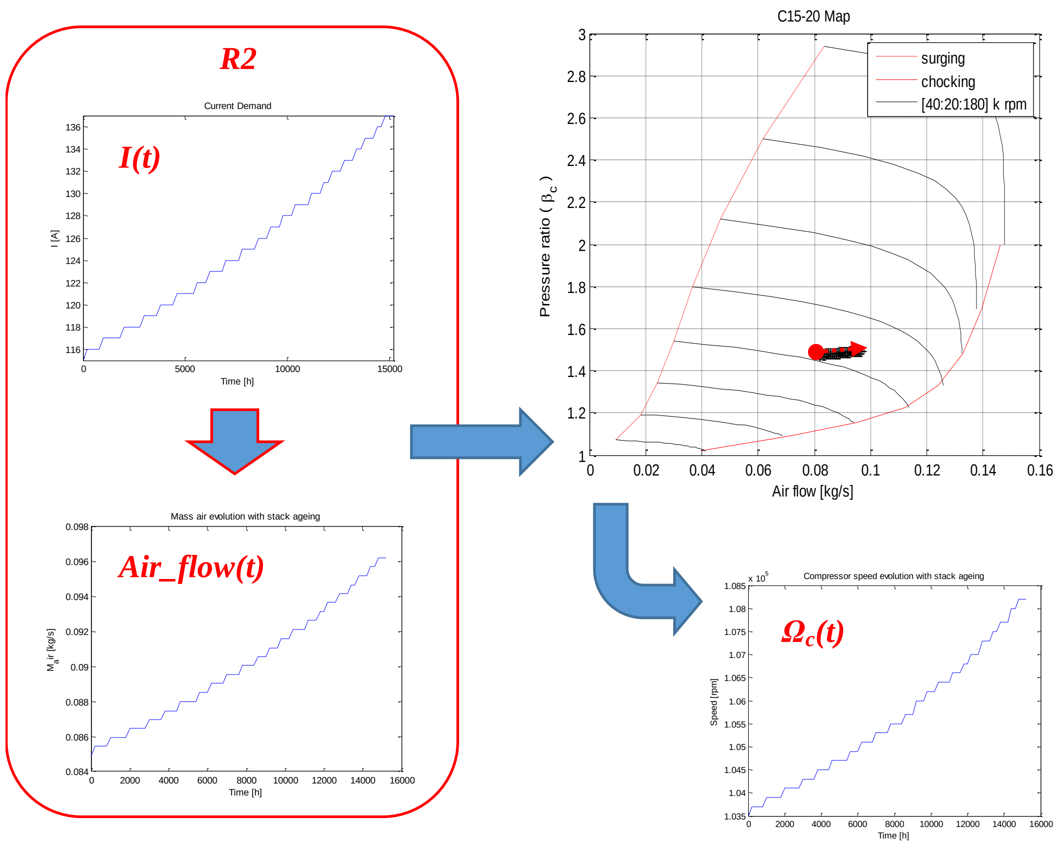

Figure 22: Air compressor operations variation related to the PEMFC ageing.

As reported in algorithm 2 (Fig. 19) description, at this level a check is required.

1. In case the BoP key-element shows a predictable ageing:
    - The component ageing is integrated into the performance variation induced by R2 (refer to Figure 23.a).
    - The related damage is evaluated.
    - The component RUL is evaluated.
2. In case the BoP component doesn't have a predictable ageing or a lack of information occurs, a FC RUL based diagnosis procedure is scheduled as mitigation measure:
    - The performance variation induced by R2 is assumed as reference profile.
    - Threshold are evaluated considering -/+ 5A of variation into the PEMFC current demand to couple with the R2 profile (refer to Figure 23.b).
    - The component operations are monitored on-board:
        - If the measured points are in the thresholds range, the related component is correctly operating to fulfill the aged stack demand.
        - If not, a malfunctioning is occurring: an alert is generate and expertise is required.

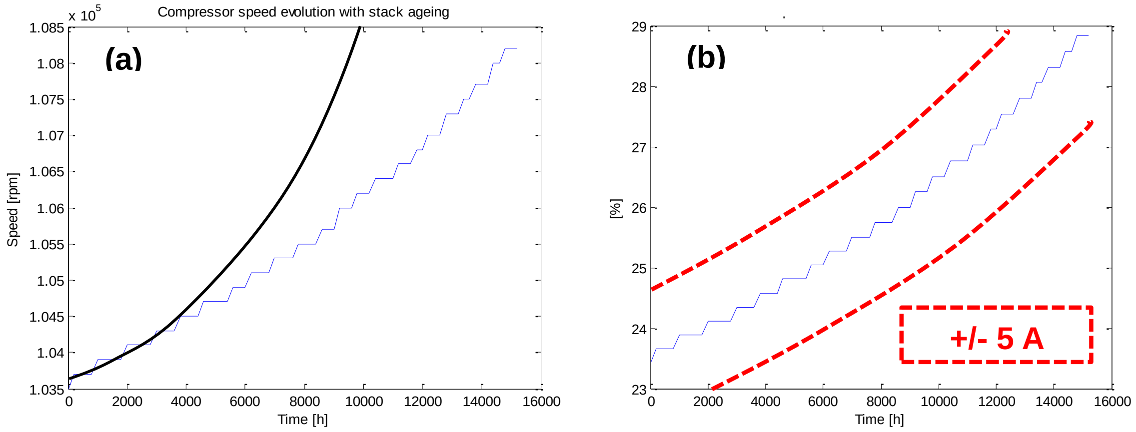

Figure 23: Performance variation for RUL extraction in case of predictable ageing (a); performance profile for mitigation strategy in case of unpredictable behavior (b).

4 Conclusion

This deliverable reports the model-based prognostic approach developed in the framework of the GIANTLEAP project. To this purpose, the relevant background for the model implementation was presented and different hypothesis based on real system configuration and available data are introduced. The model structure and the related algorithms have been presented in the following order: the global structure, the PHM/control interface, the main PHM algorithm, the key-elements simulators' algorithms and the RUL algorithm. First simulation results based on the project' available data showed the capability of the model to take into account the interactions between the PEMFC ageing and the BoP components operations.

It is worth noting that the global structure of the model is developed. However, the ageing tests for model tuning are in progress. Therefore, the final configuration of the presented EMR model and PHM algorithms could change depending on the data and information available for model tuning. In case of a lack of information occurs, a backup procedure is also proposed. The model' final configuration will be the object of the next deliverable D2.2 (prognostic software for PEM fuel cell systems).

References

[1] Borup R, Meyers J, Pivovar B, Kim YS, Mukundan R, Garland N, Myers D, Wilson M, Garzon F, Wood D, Zelenay P, More K, Stroh K, Zawodzinsky T, Boncella J, McGrath JE, Inaba M, Miyatake K, Hori M, Ota K, Ogumi Z, Miyata S, Nishikata A, Siroma Z, Uchimoto Y, Yasuda K, Kimijima K, Iwashita N. Scientific Aspects of Polymer Electrolyte Fuel Cell Durability and Degradation. American Chemical Society 2007;107:3904-51.

[2] Lin R, Li B, Hou YP, Ma JM. Investigation of dynamic driving cycle effect on performance degradation and micro-structure change of PEM fuel cell. Int J Hydrogen Energy 2009; 34; 2369-76.

[3] Harel F, François X, Candusso D, Péra M-C, Hissel D, Kauffmann J-M. PEMFC Durability Test under Specific Dynamic Current Solicitation, Linked to a Vehicle Road Cycle. Fuel Cells 07, (2007), 2; 142-52.

[4] Wahdame B, Candusso D, François X, Harel F, Péra M-C, Hissel D, Kauffmann J-M. Comparison between two PEM fuel cell durability tests performed at constant current and under solicitations linked to transport mission profile. Int J Hydrogen Energy 2007; 32: 4523-36.

[5] Petrone R, Hissel D, Péra M-C, Chamagne D, Gouriveau R. Accelerated stress test procedures for PEM fuel cells under actual load constraints: State-of-art and proposals. Int J Hydrogen Energy 2015;40:12489-505.

[6] Jouin M, Gouriveau R, Hissel D, Péra M-C and Zerhouni N. Prognostics and Health Management of PEMFC – State of the art and remaining challenges. International Journal of Hydrogen Energy 2013; 38(35): 15307-17.

[7] Jouin M, Gouriveau R, Hissel D, Pera M-C, Zerhouni N. Prognostics of PEM fuel cell in a particle filtering framework. Int J Hydrogen Energy 2014;39:481-94.

[8] Jouin M, Gouriveau R, Hissel D, Pera M-C, Zerhouni N. Degradations analysis and aging modeling for health assessment and prognostics of PEMFC. Reliability Engineering and System Safety 2016; 148: 78–95.

[9] Silva RE, Gouriveau R, Jemeï S, Hissel D, Boulon L, Agbossou K, Yousfi Steiner N. Proton exchange membrane fuel cell degradation prediction based on Adaptive Neuro-Fuzzy Inference Systems. Int J Hydrogen Energy 2014;39: 11128-44.

[10] Morando S, Jemei S, Gouriveau R, Zerhouni N, Hissel D. Fuel Cells Remaining Useful Lifetime forecasting using Echo State Network. Vehicle Power and Propulsion Conference (VPPC) 2014, IEEE, 1-6.

[11] Lechartier E, Laffly E, Pera M-C, Gouriveau R, Hissel D, Zerhouni N. Proton exchange membrane fuel cell behavioral model suitable for prognostics. Int J Hydrogen Energy 2015;40(26):8384-97.

[12] Bressel M, Hilairet M, Hissel D, Ould-Bouamama B. Extended Kalman Filter for prognostic of Proton Exchange Membrane Fuel Cell. Applied Energy 2016; 164: 220–7.

[13] Chen H, Pei P, Song M. Lifetime prediction and the economic lifetime of proton exchange membrane fuel cells. Appl Energy 2015; 142: 154-63.

[14] Boulon L, Hissel D, Bouscayrol A, Péra MC. From Modeling to Control of a PEM Fuel Cell Using Energetic Macroscopic Representation. IEEE Trans Ind Electron 2010, vol. 57, no.6.

[15] Chrenko D, Péra MC, Hissel D. Fuel cell system modeling and control with energetic macroscopic representation. In IEEE ISIE, Vigo, Spain, 4-7 June 2007.

[16] Petrone R, Yousfi-Steiner N, Jemei S, Harel F, Hissel D, Péra MC. Model-based strategy oriented to PEMFC system prognostic for Bus transportation applications based on EMR formalism.

Poster section. 7th International Conference on Fundamentals & Development of Fuel Cells, FDFC, Stuttgart, Germany, 1-2 February 2017.
[17] ISO. Condition monitoring and diagnostics of machinery-prognostics – Part1: General guidelines, Technical Report ISO 13381-1, Int. Standard Organization; 2004.
[18] Mohammadian SH, Aït-Kadi D, Routhier F. Quantitative accelerated degradation testing: Practical approaches. Reliability Engineering and System Safety 2010; 95: 149–59.