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COMPREHENSIVE MODEL-BASED METHODOLOGY FOR FAULT DETECTION, ISOLATION AND MITIGATION OF FUEL CELL POWERED SYSTEMS

Marco Gallo[1], Carmine Costabile[1], Marco Sorrentino[1*], Pierpaolo Polverino[1], Cesare Pianese[1]

[1] Dept. of Industrial Engineering, University of Salerno, Via Giovanni Paolo II 132, 84084 Fisciano (SA), (Italy). *Corresponding author, msorrentino@unisa.it

ABSTRACT

The present paper describes an innovative and generalizable approach for applying fault mitigation strategies to fuel cell powered systems. Upon information on system State of Health (SoH) and Remaining Useful Life (RUL), the effects of faults occurring at stack or Balance of Plant (BoP) level can be mitigated via appropriate maneuvers. Model-based approach is proposed to derive useful performance-related indicators per each system component. The model comprises two main parts: a nominal part, which provides the key variables behavior in nominal conditions, and a faulty part that can be used for fault identification purposes. The framework of the algorithm firstly addresses a monitoring phase, through which residuals are computed, and if one or more residuals overcome defined thresholds, a fault detection is triggered. Afterwards, fault isolation is performed by means of a Fault Signature Matrix (FSM) and the fault identification (i.e., its magnitude and time-behavior definition) is performed thanks to the faulty sub-models. Once the fault is characterized, several strategies (each designed according to four different fault magnitudes) are considered, and the most suitable one can be chosen and applied.

Keywords: SOFC, Fault Mitigation, Diagnosis, Lifetime, Remaining Useful Life.

1. INTRODUCTION

Solid Oxide Fuel Cells (SOFCs) represent a suitable technology for clean and efficient energy conversion of chemical energy into electricity and heat. Therefore, SOFCs are candidate to become one of the most suitable alternatives to conventional energy production systems for stationary applications, cogeneration and Auxiliary Power Unit (APU) [1]. Nevertheless, high manufacturing costs and limited lifetime, particularly due to degradation processes, currently limit the market penetration of SOFCs in the market [2]. The durability of fuel cells is significantly affected by several degradation mechanisms, which reduce cell performance over time and can lead to stack failures [3]. Methods to directly observe degradation phenomena aiming at the evaluation performance losses, as well as assess their behavior over time are difficult to implement. Usually, indirect SoH indicators related to voltage decay over time and coupled with temperature trend monitoring with respect to the current density and functioning time are adopted [4]. Indeed, the effect of operating parameters, such as temperature, voltage and current density has been studied in literature, to provide a reference for the development of specific methods for advanced control and automatic on-line diagnosis. These latter can efficiently detect and isolate malfunctioning at both stack and system level [5], to develop and apply fault mitigation strategies through a high-level controller. Aiming at extending the lifetime of this technology, a fast diagnostic algorithm is fundamental to detect reversible incipient faults. Moreover a reliable fault mitigation approach based on experimental campaigns performed "ad hoc" would allow choosing suitable countermeasures to apply and help in preparing necessary maintenance actions to perform or simply shut-down the system to avoid critical and unrecoverable failures. Therefore, a suitable diagnostic algorithm should be fast, accurate and capable of discerning several faults by means of a reduced number of sensors, as tradeoff between accuracy, computational burden and costs [5]. On the other hand, a heuristic knowledge of the degradation phenomena is mandatory to foreseen their effects and behavior and identify the proper action to take so as to recover the nominal state as much as possible. Usually, there are different strategies that can be applied. The usage of models to simulate the system behavior allows reducing the system hardware costs (i.e., experiments and sensors) for diagnostic purposes, as well as undertaking different countermeasures to decide the most suitable one in terms of performance, Remaining Useful Life (RUL) and maintenance costs as well. Fault diagnosis consists in four main tasks: monitoring the main variables describing the system state, detecting abnormal

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behavior of the system, isolating the fault and the affected auxiliary elements and identifying its magnitude and evolution in time [7]. The further step entails the RUL estimation and the definition of the proper strategies to apply to prevent a possible critical failure. If this is not feasible the aim should become driving the system towards a condition, in which the detrimental effect is controlled to have the time necessary to prepare a proper maintenance action at least. Fault mitigation for SOFC is an interesting field, on which the scientific community is taking the first steps. Obviously, it is the link between the diagnostic applications and the direct industrialization of such technology, considering it as the key-phase through which a controller could take energetic and economic decisions depending on the system state and its needs. For Proton Exchange Membrane fuel cells (PEM), some works paved the path, such as that of Jia et al. [8], where mitigation strategies for hydrogen starvation are proposed and effectiveness of the approaches is studied by measuring variations of local current densities and temperatures in situ under various load change scenarios, or that of Wu and Zhou [9], in which a fault tolerant control strategy is developed to make the system tolerant for unexpected faults, such as membrane drying and flooding. As regards SOFC, in the work of Wu and Gao [10] the authors developed an optimal fault-tolerant control strategy involving a fault diagnosis module, a switching module, two backup optimizers and a controller loop, while in that of Yu et al. [11] a control strategy is proposed to mitigate the voltage oscillations and deviations during electrical faults. It is clear that the proper mitigation strategy depends on the specific detrimental effect, because it has to reduce its effectiveness and to recover the nominal trend. Therefore, a generic approach is not simple to apply. For specific faults, it is worth remarking that in [8] the authors described a novel method for the mitigation of chromium poisoning by capturing chromium vapors using Cr getters, or in [12] where it is shown that getter coating with direct contact with the cathode or separated from the cathode can mitigate the Cr poisoning. Unfortunately, a few works deal with a generic methodology. Therefore, it is extremely difficult to select a proper strategy on a real working system, due to several types of malfunctioning that can occur. Nevertheless, a proper mitigation strategy should be applied "ad hoc" depending on the nature of the fault and its magnitude. The aim of this work is to propose a comprehensive methodology for the integration of a Fault Detection and Isolation approach with an innovative Fault Mitigation strategy. Moreover, suitable guidelines will be defined to allow proper application of proposed methodology to each kind of fault, according to the physical knowledge of developers and users.

2. THE MITIGATION PROCEDURE

The target is to develop a methodology that combines the diagnostic techniques and an advanced control approach to mitigate the degradation phenomena occurring in a Solid Oxide Fuel Cell. The methodology herein presented involves several phases, as shown in Figure 1:

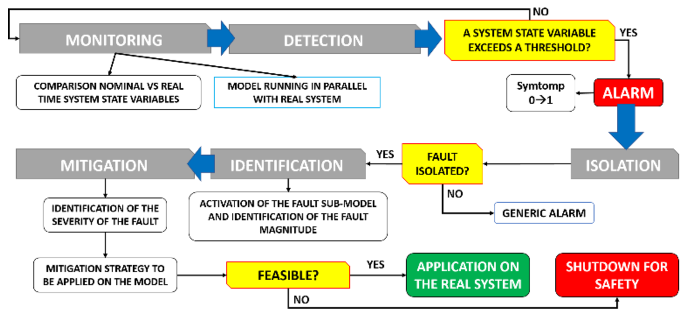

Figure 1 - Fault Detection and Mitigation algorithm phases.

All these phases need to be followed step by step to have a proper and reliable methodology aiming at facing up with occurring malfunctions and at extending the lifetime of such systems.

2.1 Key definitions

To better explain the approach adopted, some useful definitions are herein provided:

i. **System Monitoring** Specific features are computed from measurements acquired on the system. During this task only suitable data processing is performed and no inference on system status is made. The monitoring phase allows evaluating the reference conditions for the system state variable *Y* considered for each diagnostic algorithm.

ii. **Fault Detection** The extracted features are analyzed to assess if a faulty event is occurring or not.

iii. **Fault Isolation** If a fault is detected, the component(s) affected by the fault are identified and its location is determined. In this case, the diagnostic algorithm has to clearly determine which fault is and where it is located. Then, the faulty RUL (RUL_F) can be estimated. Obviously, RUL_F is supposed to be lower than the RUL_N.

iv. **Fault Identification** At this phase, the fault magnitude and its dynamics are characterized to identify its grade of severity.

v. **Fault Mitigation** According to the severity of the fault (see Figure 2), a proper mitigation countermeasure can be taken in order to have a total recovery or to change the operating condition aiming at stabilizing the detrimental effect by choosing action that are a compromise between the efficiency target needed (or the Power) and the RUL. If it is not possible and the fault can't be stabilized, a Take-Home Operation could be the most suitable solution to drive the system towards a maintenance procedure, taking time to properly face up with the problem. Moreover, if the detrimental effect is so significant that no countermeasure could improve the system condition and no Take-Home Operation can be set, an immediate shut-down is the most recommended solution to prevent critical failures.

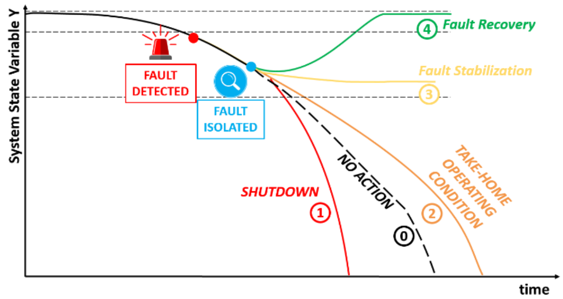

Figure 2 - Fault Mitigation approach. The system state variable *Y* behavior is the key parameter for the mitigation procedure. the black line (0) is the nominal RUL (No Action applied), while colored lines from 4 to 1 refer to the different mitigation

SYSTEM MONITORING PHASE

The system is monitored by appropriate sensors installed on-board. The system state, defined as *Y*, is the monitoring state variable that needs to be continuously observed and analyzed to infer on the SoH of the system. Its possible deviations from a nominal trust region might suggest a possible malfunctioning occurrence. Usually, *Y* is a direct measurement coming from sensors installed on-board or an indirect measurement derived from a combination of information coming from the system. A reliable monitoring approach focuses on several monitoring state variables which allow distinguishing different SoH with respect to different conditions (nominal, fault 1, fault 2, etc.). As a consequence, *Y* is a vector (see eq.(1)) containing several system states (i.e. Voltage, temperature, Fuel utilization, etc.), the more Y_i the more completed and reliable is the monitoring.

$$Y = [Y_1, Y_2, \ldots, Y_n] \tag{1}$$

Moreover, all the system state variables Y_i depend on operating variables and control ones. The control variables *u* are the variables that a controller could modify during the system running to change the functioning operating condition as the load or the input flows, while the operating variables χ are indirect variables evaluated and useful to monitor possible changes. Thus, the overall state of the system *Y* depends on χ and *u*:

$$Y = f(\chi, u) \tag{2}$$

Focusing on the meaning of the system state variable *Y*, it could be possible to theoretically split in two terms: the first one representative of the theoretical nominal conditions *G* and the second one *D*, which stands for the natural ageing of the system during its functioning. So, the equation 0 can be written as follows.

$$Y(\chi,u) = G(\chi,u) + D(\chi,u) \tag{3}$$

On a real system, it is not possible to measure *G* and *D* contributions directly, being them strictly concentrated into the measurement of *Y,* so only the overall state of the system can be measured. Thus, to account for the change of the nominal condition decoupled from natural ageing, an accurate and reliable model might help. For on-board applications the model is requested to be faster than the real system so as to provide a rapid feedback on the system behavior and its response if some inputs change. By doing so, it would be possible to consider different scenarios on the virtual machine before applying the optimal one on the real system. Defining with $\hat{X}$ a generic output derived from the model, equation (3) can be written as:

$$\hat{Y}(\chi,u) = \hat{G}(\chi,u) + \hat{D}(\chi,u) \tag{4}$$

Thus, a reliable monitoring approach would consider information from measurements taken on the real system in parallel with that one coming from the suitably validated model. In nominal conditions the system state variables *Y* and $\hat{Y}$ must satisfy the following equation:

$$|Y - \hat{Y}| < \varepsilon_m \tag{5}$$

Where ε_m is the error of the model, which in turns is representative of the model accuracy chosen. During the normal functioning in nominal conditions, performing an on-line monitoring of the system, for each Y_i the following trend will be obtained, as sketched in Figure 3.

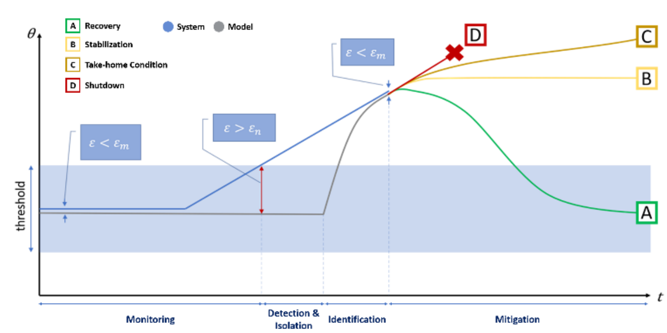

Figure 3 - Y trend during the Monitoring, Detection and Isolation phase, Fault Identification and Mitigation strategies. A) Severity grade 4 - Recovery; B) Severity grade 3 - Stabilization; C) Severity grade 2 - Take-Home Condition; D) Severity grade 1 - Shut-down for Safety.

The Blue area is the threshold for nominal conditions, suitably set upon experimental data analysis. If the system state variable is in the threshold area it can be considered as "nominal", while when Y_i exceeds the threshold, an alarm is activated, as hint of possible malfunctioning occurrence. In that case, the detection phase starts.

3. FAULT DETECTION PHASE

The Fault Detection analyses the residual between the model nominal state and the system real state. Indeed, the detection algorithm constantly compares the data measured on the real system Y_i and the simulation output $\hat{Y}_i$. The difference between the real measurement of the state and the modelled nominal condition is called Residual, R. It is the key parameter of the detection phase, because it allows to identify a possible malfunctioning in the system when it exceeds the nominal threshold. Thus, for each system state variable, a residual R_i can be defined, as:

$$R_i = \left| Y_i - \hat{Y} \right| \quad for\ 1 \le i \le n \tag{6}$$

As stated in eq.(6), considering the semi-height of the nominal threshold associated to the variable i, $\varepsilon_{n,i}$ and being it centered in the $\hat{Y}_i$, when the residual R is less than $\varepsilon_{n,i}$ (i.e. the real state Y_i is in the threshold area), the generic symptom s_i assumes zero value. On the contrary, when $Ri > \varepsilon_{n,i}$ (the real state Y_i exceeds the threshold) the generic symptom s_i associated assumes a unitary value.

$$\begin{cases} R_i < \varepsilon_{n,i} & s_i = 0 \\ R_i > \varepsilon_{n,i} & s_i = 1 \end{cases} \tag{7}$$

The symptoms collected into a vector, build up the symptoms vector. When this vector contains only zeros, it means that the system is in nominal (i.e. healthy) conditions or nothing is revealed by the detection algorithm. When one or more cells switch from 0 to 1, something is changing and the isolation phase needs to start to distinguish a missed alarm from a malfunctioning, and, in that case, to properly locate the fault. So, when in Figure 3 the residual exceeds the threshold and a symptom changes from 0 to 1. From that moment on the Isolation phase starts aiming at determining the fault occurring.

4. FAULT ISOLATION PHASE

The Isolation phase requires the heuristic knowledge of the phenomena to be accounted for in the Fault Detection and Isolation Algorithm (FDI), usually based on preliminary experimental campaign aiming at evaluating the characteristic features of such phenomena. As result, an FSM is built up. The matrix, as shown in Table 1, correlates the malfunctioning with the symptoms (whose value can be 0 or 1).

When the symptoms vector exactly matches one row of the FSM, the corresponding Fault is properly detected and isolated. During the experimental campaign and the related analysis for the FSM building, some faults could have the same row on the FSM. In that case, a redundancy of the symptoms might help in defining the fault univocally.

	STATE OF HEALTH				
	S_1	S_2	S_3	…	S_n
Fault 1	0	1	1	…	1
…	…	…	…	…	…
Fault n	1	0	1	…	1

Table 1 - Design of the Fault Signature Matrix.

Moreover, a "General Alarm" warning addresses all the not accounted faults, so as to activate an alarm when the system behavior diverges from the nominal condition, but the information available are not sufficient to properly isolate a specific fault. When the isolation phase is successfully completed, the fault F_i is clearly isolated. Thus, the model must activate the related fault sub-model, to properly simulate the faulty state, as described below. Once the sub-model is activated, the Fault magnitude needs to be identified, in order to set the correct faulty state and to infer on possible mitigation strategies to adopt depending on the nature of the malfunctioning and its stage. Therefore, the new system state variable depends also on activated fault:

$$\hat{Y}(\chi,u) = \hat{G}(\chi,u) + \hat{D}(\chi,u) + \hat{F}_i(\chi,u) \tag{8}$$

5. FAULT IDENTIFICATION PHASE

To perform a proper mitigation strategy, the identification of the fault, its magnitude and its stage is a key-point. Depending on it, the mitigation approaches can be different (i.e if the fault is at a stage which is totally unrecoverable, trying to apply recovery countermeasures might lead to a waste of time, instead of trying to stabilize the detrimental effect). Moreover, a suitable fault identification allows tuning the fault sub-model, and, in turn, the complete model, to have a simulation of the system in that faulty state. The usage of the faulty model is fundamental to infer on different countermeasures to be applied on the system before the direct application on the real system. The fault sub-model depends on characteristic parameters (A_1,A_2,…,A_n) that need to be properly identified upon real-time measurement, as described in eq. (9)

$$\hat{F}_i = F(A_1, A_2, \ldots, A_n) \tag{9}$$

Thus, a controller needs to set the optimal values of such parameters to model $\hat{F}_i$, so as to reduce the R_i lower than ε_m, satisfying eq. (5). In this way the fault identification is reached, and the model state correctly simulates the faulty condition.

Once the model is set in "Faulty mode" and tuned to simulate the current state of the system, the mitigation approach can take place. At this stage, all the optimization procedures to define the proper mitigation countermeasure need to be performed on the faulty model, while taking as reference the nominal condition model. By doing so, all the scenarios can be investigated off-line avoiding to further compromise the health of the real system. Once the mitigation strategy has been decided and defined, it will be applied to the real system, according to the constraint linked to the application for which the system is dedicated (i.e. Auxiliary Power Unit, Energy production, residential co-generation, etc.).

6. FAULT MITIGATION PHASE

According to Figure 2, four different approaches can be adopted depending on the severity of the fault. The issue is to clearly identify such state. Indeed, the detrimental effect of a fault and its irreversibility clearly depend on the intrinsic nature of the malfunctioning, its magnitude, possible hidden effects or correlation between other phenomena occurring and the quality of the FDI algorithm as well, that is the time passed between the fault occurring and its detection/isolation. Thus, once isolated the fault and identified its magnitude, the crucial step is to individuate the optimal countermeasure, as sketched in Figure 3 and the related control variables on which operate with respect to the constrains.

6.1 Severity grade 4 – Recovery

The best case for the mitigation strategy is when the system state can be restored to the nominal condition with minor changes to the RUL. This is possible when the intrinsic nature of the fault allows this kind of countermeasure and when the malfunctioning is correctly detected and isolated in a reasonable time. One of the most evident examples could be the Sulphur poisoning. At the early stage of such detrimental phenomenon the Sulphur can be removed through an active regeneration using pure hydrogen H_2 as fuel instead of CH_4 [13]. Usually, when it comes to recoverable malfunctioning, two main countermeasures can be taken. The first one is related to a process that has to be enabled to get rid of contaminants or, in general, the main cause of the detrimental effect, by imposing specific flows or switching on OCV conditions or even to SOEC mode. On the other hand, a good approach to restore a nominal condition is finding a proper set of new operating conditions, u_{new}, that annihilate the detrimental effect, with respect to constrains related to the system functioning, as performances, temperature, load, etc. In this case, the controller behind the mitigation phase needs to identify the optimal set of such u_{new} variables so as to zeros the fault F_i, as stated in the equation below.

$$\begin{gathered}\exists u_{new}\left|\hat{\mathrm{F}}_i(\chi,\mathrm{u}_{\mathrm{new}})\rightarrow 0;\quad \hat{\mathrm{G}}(\chi,\mathrm{u}_{\mathrm{new}})\approx\hat{\mathrm{G}}(\chi,\mathrm{u})\right.\\ \hat{Y}(\chi,\mathrm{u})\ \approx\hat{Y}(\chi,\mathrm{u}_{\mathrm{new}})=\hat{\mathrm{G}}(\chi,\mathrm{u}_{\mathrm{new}})+\hat{\mathrm{D}}(\chi,\mathrm{u}_{\mathrm{new}})\end{gathered} \qquad (10)$$

As a result, once defined the new set u_{new}, the system will return to a nominal state $\hat{Y}(\chi,u)$. Unfortunately, in most cases the term $\hat{D}$ refers to the ageing of components, related to the functioning time of the system and thus not recoverable.

6.2 Severity grade 3 – Stabilization

Sometimes, the minimization problem related to the u_{new} that zero the fault $\hat{F}(\chi,u)$ has no feasible solutions; thus, the complete recovery of the nominal operating conditions results not achievable. In that case, the mitigation process should identify a solution that allows reducing as much as possible the detrimental effect and thus extending the RUL. The goal is to stabilize the $\hat{F}_i$, considering to set a new condition, different from the nominal one, that has a good compromise between performance and extended life, within the constrains, as described in the equation below.

$$\begin{gathered}\exists u_{new}\left|\hat{\mathrm{F}}_i(\chi,\mathrm{u}_{\mathrm{new}})\neq 0;\ \hat{\mathrm{G}}(\chi,\mathrm{u}_{\mathrm{new}})\neq\hat{\mathrm{G}}(\chi,\mathrm{u})\right.\\ \hat{Y}(\chi,\mathrm{u})\ \neq\hat{Y}(\chi,\mathrm{u}_{\mathrm{new}})=\hat{\mathrm{G}}(\chi,\mathrm{u}_{\mathrm{new}})+\\ +\hat{\mathrm{D}}(\chi,\mathrm{u}_{\mathrm{new}})+\hat{\mathrm{F}}_{\mathrm{i}}(\chi,\mathrm{u}_{\mathrm{new}})\end{gathered} \qquad (11)$$

To have a stabilization, from a mathematical point of view, the u_{new} must zero the derivative of both the fault and the theoretical nominal conditions $\hat{G}$:

$$\frac{d}{dt}\left|\hat{\mathrm{G}}(\chi,\mathrm{u}_{\mathrm{new}})+\hat{\mathrm{F}}_{\mathrm{i}}(\chi,\mathrm{u}_{\mathrm{new}})\right|\approx 0 \qquad (12)$$

6.3 Severity grade 2 - Take-home Condition

If even the stabilization approach fails (see eq. (13) due to a sensible detrimental effect, the focus must be the maintenance to replace the damaged component and restart as soon as possible the system.

$$\frac{d}{dt}\left|\hat{\mathrm{G}}(\chi,\mathrm{u}_{\mathrm{new}})+\hat{\mathrm{F}}_{\mathrm{i}}(\chi,\mathrm{u}_{\mathrm{new}})\right|\neq 0 \qquad (13)$$

In this case, a change in the operating conditions would be beneficial in extending the RUL to give the time to prepare the maintenance τ_{ptm}. This condition is defined "take-home condition". Usually, a common take-home condition is the switching to OCV mode or to a very small load, providing with two main benefits. Indeed, interrupting the electrical production without shutting-down the system allows avoiding the fast degradation correlated to a phenomenon occurred (i.e. a hotspot in the cell leading to anode re-oxidation) and not sensibly reducing the operating temperature as well. An analysis in the efficacy of the mitigation application needs to be done regarding the RUL. If the countermeasures allow extending the RUL of the system for a time window at least sufficient to prepare the maintenance (i.e. replacing a stack or changing a stack component), as reported in eq. (14) it is worth applying the mitigation.

$$RUL_{new} > RUL_0 \quad \rightarrow RUL_{new} > \tau_{ptm} \tag{14}$$

6.4 Severity grade 1 - shut-down for safety

If the best solution offered by the mitigation approach does not ensure a reasonable increase in the RUL, the system has to be shut-down for safety reasons, even if this implies that the system will not be able to provide energy (eq. (15)).

$$\begin{gathered} \frac{d}{dt}\left|\hat{\mathrm{G}}(\chi,\mathrm{u}_{\mathrm{new}})+\hat{\mathrm{F}}_{\mathrm{i}}(\chi,\mathrm{u}_{\mathrm{new}})\right| \neq 0 \\ RUL_{new} \leq RUL_0 \quad or \quad RUL_0 \leq \tau_{ptm} \end{gathered} \tag{15}$$

This does not mean that the mitigation approach has failed. On the contrary, a reliable approach, thanks to its monitoring and detection algorithms, will provide an estimation of the RUL, and the identification of the severity of the fault will help the maintenance in the decision making of the component replacing or the entire system changing as well. In Table \ref{tab:2}, a sum-up of the mathematical key parameters of such approach are linked to the different stages and objectives of the mitigation strategy.

	Recovery A	Stabilization B	Take-home Condition C	Shutdown for safety
Severity	4	3	2	1
RUL$_{new}$	$>>\tau_{ptm}$	$>>\tau_{ptm}$	$>\tau_{ptm}$	$<\tau_{ptm}$
$\hat{F}_i$	0	≠0	≠0	≠0
dF$_i$	0	0	≠0	≠0

Table 2 - Mitigation table for decision making parameters

7. CONCLUSIONS

Model-based design of an innovative and generalizable fault mitigation strategy was proposed. The main targets of the approach are fuel cell powered systems. The exploitation of proper system component models for the definition of SoH and RUL, allowed a prompt and precise identification of the RUL under nominal and faulty conditions. Such information is taken as indicator for choosing the mitigation strategy level to be applied to fulfil: i) full recovery, ii) stabilization, iii) Take-home condition or iv) safety shut-down. The theoretical approach and framework of the proposed strategy can be related to any kind of system affected by fault, thus ensuring a general and flexible tool that can be easily modified and updated according to the needs. Future updates of the work will entail the verification of the feasibility of the proposed approach on practical cases under different faults magnitude and the extension to other cases/technologies.

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