Corrective Action with Power Converter for Faulty Multiple Fuel Cells Generator used in Transportation

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***Abstract*—This paper deals with the corrective action with a power converter for a 100kW multiple fuel cells (FC) generator under fault and used for vehicle propulsion, or high power onboard electrical assistance. The objective is to permit, through the power converter and its control strategy, a soft shut-down of a FC stack in fault and guarantee a continuous of operation at a reduced power, acceptable by the specifications. The power converter should also realize the power management during the degraded working situation. Two power system architectures are studied and compared by numerical simulation.**

Keywords- Fuel cells, redundancy, continuous operating, operational reliability, degraded working mode, power managment.

I. Introduction

In the current economical and environmental context, many researches are focused on clean energy or clean vehicle. Fuel cells (FC) fed by hydrogen/air are an alternative for electricity generation for different applications: stationary, embedded, transport and APU. Fuel cells produce only electricity, heat and water, which make them very environment friendly.

Generally speaking fuel cells are low voltage, high current electrical generator. Moreover FC voltage drops significantly while its current increases (the FC voltage at its rated current is roughly half of its open circuit voltage). Most applications require a power converter in order to increase and regulate the output voltage. In transport applications, FC is evaluated as an energy conversion source. In order to deliver power traction demand, FC can be hybridized with batteries or ultracapacitors [1] and prototypes of car, bus or train have already been designed [2-3].

Currently polymer electrolyte membrane fuel cells (PEMFC) seem to be the best technological solution for fuel cell integration in vehicle. Many reasons can be listed to explain this choice. Among them its solid electrolyte, well adapted for transport and vibrations, its high power density and its low temperature (resulting in a rapid start up) can be outlined. Nevertheless, power generation for traction application requires high power generator. For this purpose, FC manufacturers need to design specific FC with large membrane electrode assembly (MEA) and an important number of cells. But high power stacks have technical limitations. They are difficult to operate because of an inhomogeneous fluidic distribution. Moreover, very long stack might lead to mechanical problems that may cause gas leak. Furthermore, fluidic problems may cause local sub-stoichiometry or can affect the water content in the fuel cell causing flooding or drying. All these problems could result in a dramatic power loss, and even worst in permanent damage. High power and reliable fuel cells are needed, particularly in transport applications. Thus the association of multiple small scale fuel cells in order to deliver high power seems to be a good way to get in [4]. Consequently a great deal of FCs connection is conceivable. Thanks to the multi-stack association, if one stack gets out of order it can be shut down allowing the other fuel cells to continuously deliver the load power. Thus, it is possible to build a fault tolerant generator. Hence, the system designer has to evaluate all the series and/or parallel associations in order to find out the best electrical architecture and conceive the related coupling power converter.

Finally, in order to design a fault tolerant fuel cell architecture, on-line fault detection on the fuel cell generator needs to be performed. Many techniques exist based on the fuel cell impedance measurement thanks to electrochemical impedance spectroscopy (EIS) analysis, cyclic voltammetry (CV) and current interruption (CI) [5-8]. They provide good information about the FC state of health (SOH) but are long to perform. To achieve very fast fault detection, a voltage based detector can be a good agreement. Indeed, some faults can occur in localized areas of the stack. Thus, a judicious monitoring using only a few numbers of cells allows the detection of the fault. The authors propose in [9] fault detection thanks to localized voltage measurements. With this technique, named the differential technique, it is possible to quickly detect a fault. This technique can be monitored on-line, used only a few sensors and is non-intrusive.

The article is organized as follows. First it presents specifications of the multi-stack fuel cell system including the definition of the degraded working mode. This part contains a state-of-the-art part focused on the feedback experience for FC demonstrators in the transportation domain; the problematic of the optimal configuration for FC architecture used in transportation, and a FC model is presented. After that, two technological solutions are successively detailed: The use of one single converter for multiple stacks is evaluated. Then the case of one converter per stack is analyzed. All the cases are studied and compared by simulation using Matlab-Simulink software.

II. SPECIFICATIONS

A. Feedback experience for FC vehicle demonstrators in transport applications – an overview

Fuel cells have already been tested and evaluated in many transport application as demonstrators around the world (USA, Canada, Europe, Japan…). The European Commission set out to develop and demonstrate an emission-free and low noise transport system with the CUTE project (Clean Urban Transport for Europe). For this aim, 27 Hydrogen powered fuel cell buses were built and used in 9 European cities for 2 years. Fuel cell maximum power is 200kW and the average consumed power during their 7000hrs of service is 73.5kW [10]. In parallel the ECTOS project (Ecological City TranspOrt System) was led in Iceland. It demonstrates the use of 3 hydrogen fuel cells buses in regular transport public. The fuel cell is a 250kW PEM system from Ballard [10]. In California many fuel cell buses were tested since 1999. The buses company AC Transit and SunLine Transit Agency are testing buses equipped with a 120kW fuel cell generator [11-12]. Since December 2009, 20 buses powered by a 150kW fuel cell power system are operating at Whistler, Canada, for the 2010 winter Olympic Games and will continue afterwards. It is the largest hydrogen fleet of fuel cell buses in one transit location [12]. In France, the GENEPAC project was run in order to design and build a fuel cell for automotive applications. It focuses on the development of a compact fuel cell stack with high output dynamic performances [13]. The French research project SPACT-80 was led to design and manufacture a robust and durable air/H_2 80 kW PEM fuel cell-based system, specifically developed for railway and road applications. Generic tests have been performed over several fuel cell modules which power is ranging from a mini-stack to a 30kW air/H2 power stack [14-16]. Fuel cells have been evaluated on hybrid locomotive demonstrator [17] and on the four-wheel-drive hybrid demonstrator truck “ECCE” (“Evaluation des Constituants d’une Chaîne Electrique”). As other examples of the application of FC in the railway area, a fuel cell hybrid locomotive is presented in [18]. Powered by 2 FC stacks which deliver a continuous power of 250kW, the locomotive can produce a transient power up to 1MW thanks to the hybridization. This makes the locomotive the heaviest and the most powerful fuel cell land vehicle. In Japan, a test running of a railway vehicle equipped with 100-kW fuel cells has been also performed [19].

B. Optimal configuration for FC generator architecture used for transport application (for continuous operating)

As a practical specification example representative of transport application, the electrical generator should be able to deliver a power of at least 80kW, with a DC voltage bus of 540V. For this study, a set of 4 fuel cells modules is taken into consideration. Each module can deliver a power of 28kW in order to obtain a maximum power of 112kW. One stack consists of 90 cells with an active area of 500cm². Rated voltage of one stack is 60V for a current of 400A; its open circuit voltage (OCV) is 92V. No matter how is the fuel cell association is realized, we consider that each FC stack has its own gas regulation. In order to increase the output voltage, the FCs are connected in series. Hence the rated voltage of the whole association is 240V and the total open circuit voltage is 368V. Consequently the elevation ratio of the required converter varies between 1.4 and 2.25. A classic boost converter is well adapted for these values, and there is no need of a transformer.

Specification allows a degraded mode. This means that during the failure of a FC, not all the nominal power has to be delivered. In this mode, only a minimal power is required in order to power only critical device like propulsion system and perform a continuity of service. Then as the SPACT-80 project already did, the operation under degraded mode is specified as a power supply reduction of no more than 75% of the rated power. In this case, it means that the load tolerates the loss of one entire stack.

In the system there is a supervisor. Its aim is to notify to other system devices that a fault occurs. In our case, after fault detection, the supervisor will limit the power consumed by the system according to the power loss of the generator by limiting the current reference of the devices (i.e. shedding of non-critical auxiliary). It is the degraded mode. It can act on the converters depending on the FC association topology. Fig. 1 scheme shows the different components involved in the system (FC, power converters, supervisor) and outlines the problematic of the suitable coupling between the FC source, the power converters and the supervisor. The figure presents the fragmented synoptic of the multi-stack fuel cell electrical generator.

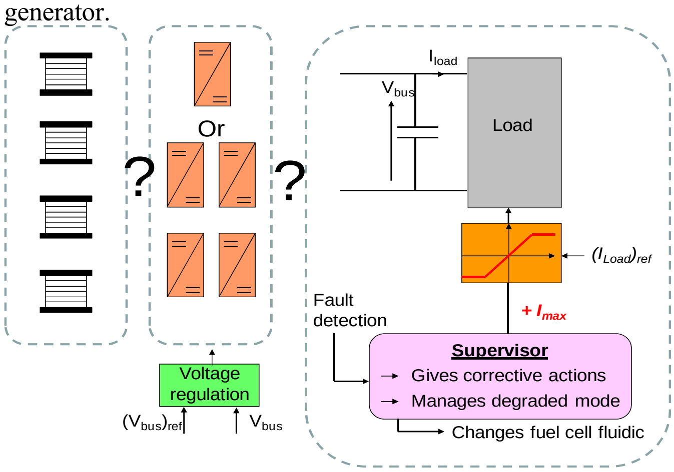

Figure 1. Fragmented synoptic for an optimal configuration of a multiple FCs generator, power converter interface and supervisor system.

C. Fuel cell modeling

As the FC voltage is highly dependent of its current a fuel cell model is required. The same cell model than [9] is used, and is based on the static voltage equation:

$$V_{cell} = E - \eta_{act} - \eta_{ohm} - \eta_{conc.} \quad (1)$$

Where E (V) is the electromotive force,

η_{act} the activation voltage which represents the fact that some energy is needed to generate a reaction product:

$$\eta_{act} = (R\, T_{fc}) / (2\, \alpha\, F).\ ln(\ (J+J_n)/J_0\ ) \qquad (2)$$

J is the fuel cell current density, J_n the leakage current density, J_0 the exchange current density, R the perfect gas constant, T_{fc} the cell temperature, α the charge transfer coefficient and F the Faraday's constant.

$\eta_{ohm.}$ the ohmic voltage which is due to the resistance for both electronic and ionic currents.

$$\eta_{ohm} = R_{mem}\ .\ \ J \qquad (3)$$

η_{conc} the concentration voltage which is due to a mass transport limitation at high current density.

$$\eta_{conc} = m.\ exp(n\ J) \qquad (4)$$

Many faults can occur in a fuel cell, but we will focus on a reversible fuel cell fault (i.e. a fault that doesn't permanently damage the fuel cell). A fuel cell during a reversible fault can be restored with an action on fuel gas and/or with an electrical action. Reversible faults are flooding, drying and some cases of poisoning. Flooding, due to an excess of water in the cells inhibits gas transport to the reaction sites and reduces the surface area of the catalysts [20]. It virtually reduces the active area and is simulated by a modification of the cell surface S_{fc}. On the contrary, a drying situation results in an increase of the membrane resistivity [21]. It is simulated by an increase of the membrane resistance. Poisoning is owing to the quality of gaseous hydrogen (H_2) or air. If contaminants are present in the gas then they cause performance degradation of the fuel cell [22]. As already mentioned, a failure does not affect the entire stack but only some localized cells or group of cells. Thus a flooding occurs in the inlet or outlet of the stack and a drying will occur in the middle of the stack [23]. This implies that the stack voltage will not be much impacted during the beginning of such faults. In the following section a flooding failure will be simulated but a drying would induce the same global voltage change [24]. A voltage drop in the faulty cells occurs and thanks to the differential technique, a voltage measurement of groups of cells located in the inlet, center and outlet, the fault is quickly detected [9]. During a failure, it is important to reduce the current through the cell in order to increase its voltage. Furthermore, it prevents of the failed cells overheating.

D. *Fault diagnosis techniques:*

Lots of researches are on the fault diagnosis of PEMFC. In [25] the authors propose fault detection thanks to a fuzzy diagnosis model. It is designed to detect in preference two kinds of faults: the accumulation of nitrogen and/or water in the anode and an important drying. Thus the model needs only the voltage and the current in order to detect a fault. Another model based fault detection is presented in [26]. The detection is based on computing residuals obtained comparing measured inputs and outputs with analytical relationships, which are obtained by system modeling. In [27] the instantaneous load current, the temperature and fuel/gas source pressures of the fuel cell are measured and are fed into a dynamic model. Then if measured voltages cell differ from the model voltage by employing the Hotelling T^2 statistical analysis then a fault is detected. A Bayesian network for fault diagnosis is presented in [28], the fault records of some characteristic variable is an important part of the method.

Flooding or drying fault detection is proposed by [29] thanks to EIS measurement. The author shows that drying modifies the FC impedance over a large frequency range counter to a flooding which modifies FC impedance only in low frequency. Then measuring a high and a low frequency band allow a detection of these two faults. Thanks to two equivalent model of the fuel cell impedance, the authors in [30] propose a detection of flooding, drying and catalyst poisoning faults. The first model describes the behavior of the PEMFC during its normal operation and during a flooding operation. The second model describes the two other faults. A fuel cell impedance model is also used in [24,31] and allows detecting real time flooding and drying.

In [32], the authors use pressure drop in the fuel cell to detect flooding faults. The authors in [33] propose flooding fault detection with cell monitoring. In low current density a current spike of at least $0.5A/cm^2$ is performed, then if measured voltages cell differ from the median cell voltage anode flooding is suspected. Voltage monitoring is proposed by [34]. Cell voltage monitoring is an appropriate fault detection, but is not enough for determining the fault cause. Finally in [9] voltage based fault detection is presented. Thanks to three localized measurements (in the inlet, the center and the outlet), a flooding or a drying can be detected.

III. One converter for multiple stacks

A first study is carried out with a direct connection of the four fuel cells in series. Series connection allows a higher converter input voltage. Voltage bus (V_{bus}) is regulated to 540VDC and the load is set to a constant power of 80kW. Voltage regulation is implemented with 2 imbricated loops. The inner loop is a current loop, it regulates the FCs current, and the outer loop is the voltage regulation loop. Fig. 2(A) shows the synoptic of the system with supervisor.

A flooding is simulated in the inlet cells of one stack. As only a few numbers of cells are impacted in a stack, the stack voltage decrease is not significant. When the fault is detected, the supervisor can only intend to reduce the current of the faulty stack. This decrease aims to protect the stack and helps to prevent the failure progression. In addition a fluidic action on the fuel cell will allow the stack to recover a healthy state.

Nevertheless, this topology faces a drawback. As far as the FCs are in series, reducing the current of one stack results in decreasing the current of all stacks. Thus this emergency action relieves the failed stack but also the healthy ones. As a result the load has to face unnecessary power loss. Furthermore, due to the specifications, the supervisor can't reduce the power under 75% of the generator power which implies that the stack current can't fall under a certain value. So this could prevent a fast restore of the faulty stack. Finally, if the fault is not corrected and expands, the stack needs to be shut down in order to be protected. In this specific case the entire generator has to be shut down because of the series connection. To prevent this drawback a derivative circuit is needed, which conducts to the second topology.

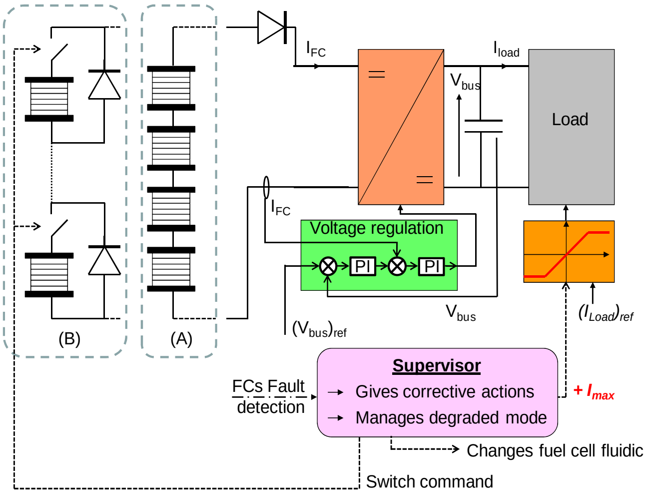

Figure 2. Synoptic of the one converter architecture (A) 4 Fuel Cells, (B) 4 Fuel Cells with by-pass circuit).

The previous topology is upgraded by adding one power switch in series and one diode in antiparallel to each stack (Fig. 2(B)). With this second topology, the previous operation remains achievable, but it is also possible to by-pass the faulty stack [35]. When a fault occurs, the faulty stack is instantaneously shut off and its current is directly by-passed through the diode. As the faulty stack delivers any current more, it could easily restore a healthy state. Of course, while by-passing the faulty stack, the supervisor has to limit the load power to remain the energy balance and prevent the bus voltage from dropping. Fig. 3 shows the failed stack voltage and current during a by-pass, a healthy stack voltage, the converter output voltage and the load power. A fault is detected at 2.5ms, the load is decreased from 80kW to 60kW, and the faulty stack is by-passed. One advantage of this technique is the step current interruption that can be observed on the faulty stack. Indeed, FC is electrochemical converter and a current interruption allows to measure fuel cell impedance thanks to the voltage response. This way it is feasible to precisely indentify whether the fault is a drying or a flooding [5].

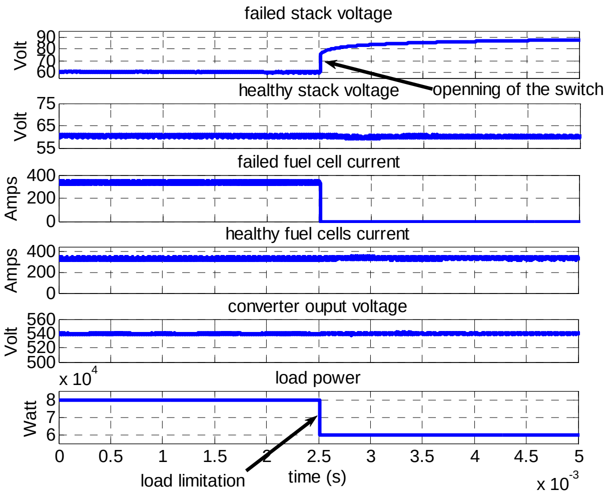

Figure 3. Voltages and currents during faulty stack by-passing.

Nonetheless the major drawback is the restart of the previously faulty stack. Once it has recovered a healthy state, it needs to be reconnected to FC system. Fig. 4 shows voltage and current of the reconnected stack while the load power is kept to 75% of the rated power. When the switch is closed, the current takes place instantly in the fuel cell. Because of external auxiliary devices for gas regulation, fuel cell response time is wide compared to electrical response. In consequence step current could damage a FC [36]. For this reason hard restart is not conceivable and can bring the fuel cell back into fault. A soft restart of the fuel cell is needed. In this context, a soft restart implies a shutdown of all the stacks which is unacceptable in view of the transportation specifications. Considering this second topology, restart operation (starting again a stack after removal) is a trouble; the by-pass method could be grueling for the FC. That is why another topology is suggested; this topology allows an independent power regulation of each stack.

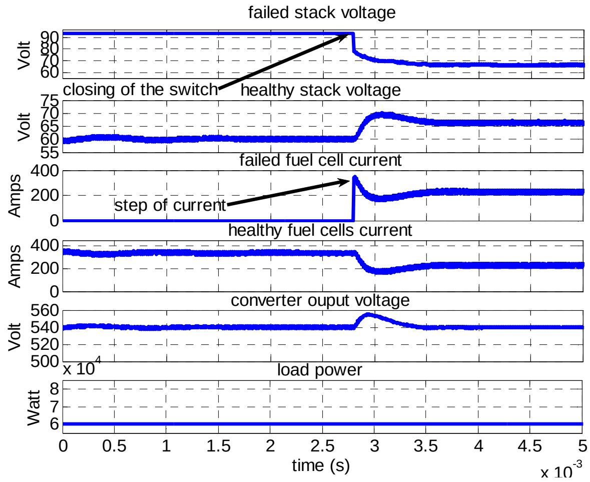

Figure 4. Voltages and currents during a restart of the faulty FC stack.

IV. ONE CONVERTER FOR EACH STACKS

This third topology associates each stack with its own converter. This architecture allows each stack to be controlled independently. Two levels for the power regulation are considered: a preliminary level only consists in sharing the power between the stacks when a slight difference appears. A second level, following fault detection, leads to significative power reduction for the faulty stack by acting on the voltage references. This action is performed simultaneously with a corresponding load reduction. We briefly describe the two methods hereafter.

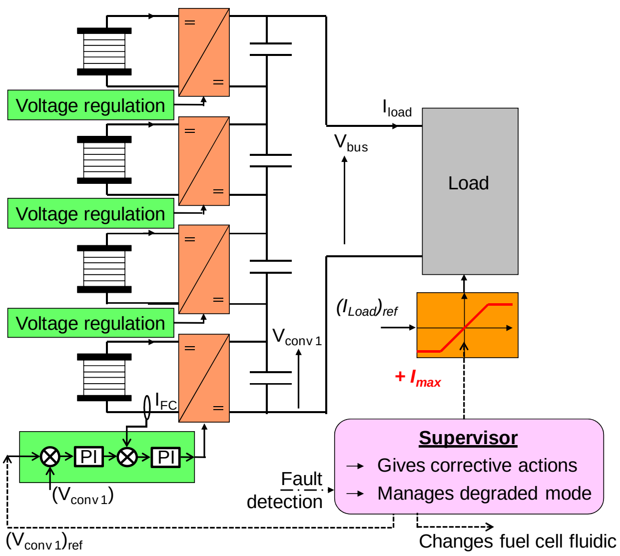

Figure 5. Synoptic of the one converter for each stack architecture.

For the first level of regulation, each converter control references are calculated according to the fuel cell voltages. The aim of this method is to slightly reduce the power delivered by a stack when its voltage drops compared to others. Thus, power delivered by the other stacks is logically increased in order to compensate the light unbalancing. An early fault does not impact significantly on the amplitude of the global stack voltage in particular when the stacks are large ones. That is why a voltage representative of the FC state is needed. The FC stacks are already instrumented in order to perform the fault detection and identification, as presented in [9], thus 3 localized voltages per stack are available. These localized voltages are also used for generating the converter control references. These 3 voltages are summed and the result is named $V_{p\,i}$ (with i=1, 2, 3, 4, corresponding to the 4 FCs). Thus converter voltage reference ($V_{conv\,i}$) is calculated as follow:

$$(V_{conv\,i})_{ref} = V_{bus\,ref} . V_{p\,i} \Big/ \sum_{i=1}^{4} V_{p\,i} \qquad (5)$$

This first level of regulation could prevent the occurrence of a fault, but remains not sufficient. The second level of regulation is therefore involved. If a fault is detected thanks to the differential technique, then a significant power reduction is induced on the failed stack. Reduction could be 1/2 or more of the stack nominal power. This relevant power decrease is done on the faulty stack in order to restore it in a brief time and an action on the fuel cell fluidic could be performed on the same time. Consequently to this power reduction, load power is simultaneously limited according to the power reduction of the failed stack. As an example, in the case of stack power reduction of 1/2 then load power has to be limited to 1/8 of the maximal power. Fig. 6 shows the current and voltage of the failed stack and of a healthy stack illustrating the second level of power regulation. The current of the failed stack is reduced, which allows a good recovery of the failed stack.

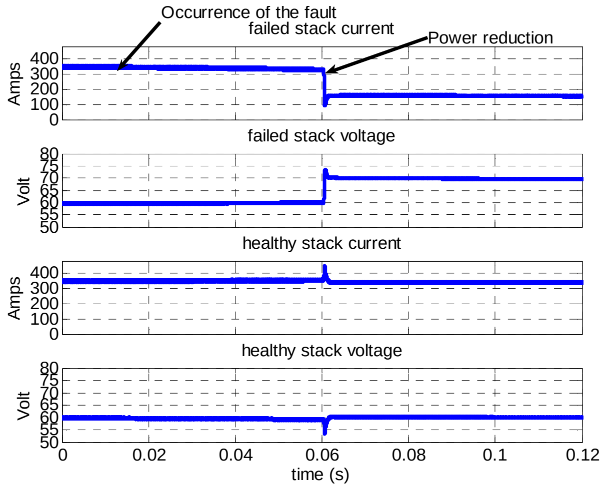

Figure 6. Stack voltage and current during power reduction.

This electrical topology allows less power reduction than the previous one presented in section III. Moreover, power reduction is fully controlled compared to the topology involving a by-pass circuit where all the stack power is instantly lost. Finally, unlike the by-pass topology when the FC stack has got back to its healthy state, it is easier to recover the full power.

V. CONCLUSION

This paper has addressed to the problematic of continuous power delivery for a multi-stack fuel cells generator used for transport application. It has taken into account the fault occurring in one of the fuel cells and the corrective action performed with the power converter in order to manage the fault and allow operating under degraded working mode. Two electrical topologies for the FC generator and its power converter interface have been presented and analyzed by numerical simulation. The first topology concerns the FC stacks in series with only one converter, adding also a by-pass circuit. The second one includes one converter per stack, which authorizes an independent power regulation for each stack and permits a softer shut-off then a better health recovery state in this case.

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