THE BACKGROUND OF A DEDICATED ON-SITE CELL VOLTAGE MONITOR FOR FUEL CELL SYSTEMS

Grietus Mulder, Peter Coenen, Dominique Weyen, Geert Jacobs, Fjo De Ridder
Vlaamse Instelling voor Technologisch Onderzoek, Boeretang 200, B-2400 Mol, Belgium

This paper is an abstract of a full-length article published in International Journal of Hydrogen Energy, 22-9-2008, available on-line at ScienceDirect.com .

In the original text more explanation and examples are given, including references.

Abstract

Laboratory high performance test equipment is too expensive and bulky for on-site fuel cell stack evaluation. Yet safety assessments show that cell voltage monitoring is a crucial element in operating a fuel cell system. In this paper a dedicated cell voltage monitoring system for on-site applications is evaluated. It describes the specific concept of the on-site monitoring system, shows measurement results for safety, control and long-term evaluation and presents a comprehensive comparison with laboratory equipment.

1. Introduction

The aim of this paper is to compare an on-site cell voltage monitoring system with R&D equipment. First, the concept of the on-site cell voltage monitor is discussed. Next, measurements are evaluated for three purposes, i.e. safety, control and long-term evaluation. Finally, communication protocols for the on-site monitor are compared.

2. Fuel cell monitoring

Several ways exist to monitor fuel cell behaviour as described in an elaborate review on diagnostic tools and in fuel cell explanatory books. The measurement methods that can be applied on a normal (non-adapted) stack are: polarisation curve, current interruption, electrochemical impedance spectroscopy and pressure drop measurement. From these methods only pressure drop measurement can be applied to an on-site stack. The other methods need an active interference in the electrical load of the stack. For an on-site stack that follows the load withdrawn by a user, this intervention is difficult to implement without influencing the user load. For current interruption, for example, it necessitates electrical energy storage. Impedance spectroscopy for stacks on top of user load is less drastic while it concerns a small cumulated AC voltage or current. The obtained frequency information is a clue to the operating condition of the stack, e.g. drying or on the contrary, flooding of cells. Despite the diagnostic prospect, impedance spectroscopy for large stacks is limited, due to cost and the challenge of imposing a current ripple.

Due to the dilemmas above, on-site stack monitoring is mainly confined to cell voltage monitoring. The cell voltages in a stack can already be different under steady state conditions due to the position of the cells in the stack. Cell voltages react rapidly and sensitively to stack condition changes, making them suitable for safety monitoring and control. Although the complete fuel cell stack should react on changing conditions, our experience is that there are cell groups in the stack that respond more quickly due to their (un)favourable position in the stack, enabling detection before the stack voltage significantly alters. In addition, single cell voltages can decline as a result of internal occurrences like a water droplet hindering gas flow or a pinhole in a membrane.

3. Concept

The dedicated cell voltage monitor CellSense consists of scanning units that send the individual cell voltage information to a monitor controller that processes it into summarising messages. The monitor retransmits to the controller of the fuel cell system via CAN or RS232 (Fig. 1). The technique behind the monitoring system has been patented. In this section a brief explanation is given to provide a basic understanding of how the monitor works and gives the background for interpreting the measurement results. It describes the electronics and how this differs from conventional laboratory set-ups.

The scanning unit is one analogue-digital (AD) converter per 4 cells. This has the advantage that

– it makes the monitor modular, i.e. as many converters as desired can be added, so that it is easily adaptable to the stack size;
– it resists a high common mode voltage, accordingly it can be used in large stacks or multi-stack configurations;
– it enables simultaneous measurement, consequently it avoids false alarms when the stack current changes rapidly.

Alternative methods found in literature make use of multiplexer configurations with voltage divider or resistor-diode combinations. However, these methods suffer in scan rate for basic (low cost) multiplexers, so that it can take seconds to measure the whole stack. This makes comparison of cell voltages under rapid load changes almost impossible. In addition, galvanic isolation is only feasible with expensive components.

The lay out of the electronic board of the monitor is flexible, as shown in Fig. 2. It is typically adapted to the stack size and mounted directly on top. All cell voltages are measured instantaneously including below zero Volt (cell inversion). The latter is due to the fact that each scanning unit has its own reference point of voltage. The sensing side can withstand the combined voltage levels of several stacks, i.e. up to 250 V. For the communication channel, a double galvanic insulation (up to 3 kV) has been realized to provide a barrier in a multi-stack-arrangement.

In the next sections the use of the cell voltage monitor for safety, control and long-term evaluation is described, together with an analysis of specific measurements.

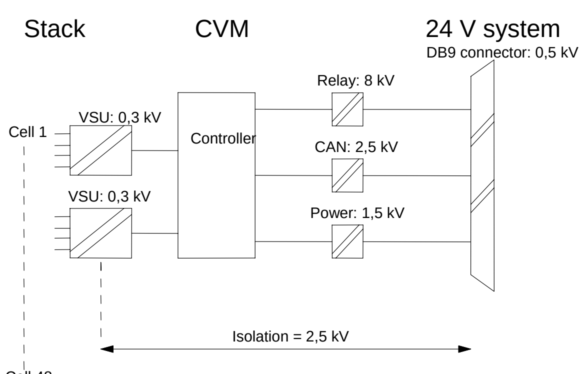

Fig. 1 – The cell voltage monitor lay out with indication of the common mode voltages that can be resisted.

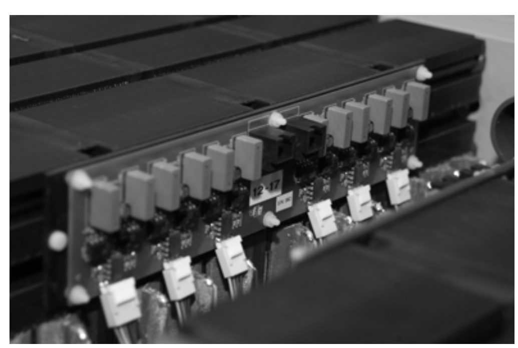

Fig. 2 – A typical arrangement of the cell voltage monitor on a stack.

4. Safety

Incorrect gas flows, low humidification, internal stack damage and short circuits, amongst others, can cause failures or errors in low-temperature fuel cells such as PEM and alkaline. Such breakdowns can often be avoided by managing the operational conditions. An important indication of malfunction is the decrease in cell voltage levels. Most failures or error situations can be detected by monitoring the lowest cell voltage. For this reason, a cell voltage monitor is mandatory for on-site fuel cell systems. On top of this, the detection of low cell voltage is the predominant cause of stack shutdown.

For safety purposes the monitor in this article is equipped with a configurable (fail-safe) relay output. The relay can be integrated in an emergency circuit that can for example switch off the fuel cell system's power.

There are two issues that we consider important to guarantee a safe operation: measurement range, and scanning rate. This is clarified in the next paragraphs, in which one example is given for measurement range importance. In addition examples show how a failure situation is reflected in the cell voltage levels.

Regarding the measurement range, it ranges from -0.1 to 1.1 V. In systems where cell voltage inversion can arise under start-up conditions, like in alkaline fuel cells with a liquid electrolyte, it is recommendable to measure also negative voltage in order not to start-up the system immediately but to adapt the start-up strategy. Fig. 3 shows this situation. Inversion is due to an electrical circuit while the cell receives no or not enough hydrogen. An action can be purging with hydrogen during a longer period or more intensely.

For failure detection, the scan-rate is important. The conversion rate for multiplexing equipment like all laboratory multi-channel meters is confined. This can be an obstacle in multi-stack systems with over 100 cells or in dynamic load applications as fuel cell systems in vehicles. Our cell voltage monitor scans at a rate of 1000 cells/s in order that e.g. a 100 cell stack can be scanned at 10 Hz.

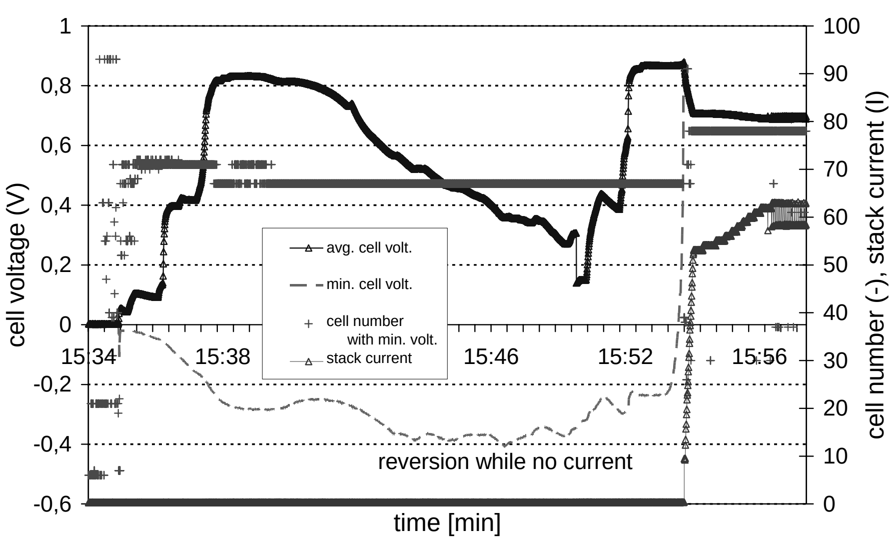

Fig. 3 – Cell voltage reversal at start-up, detected by the cell voltage monitor.

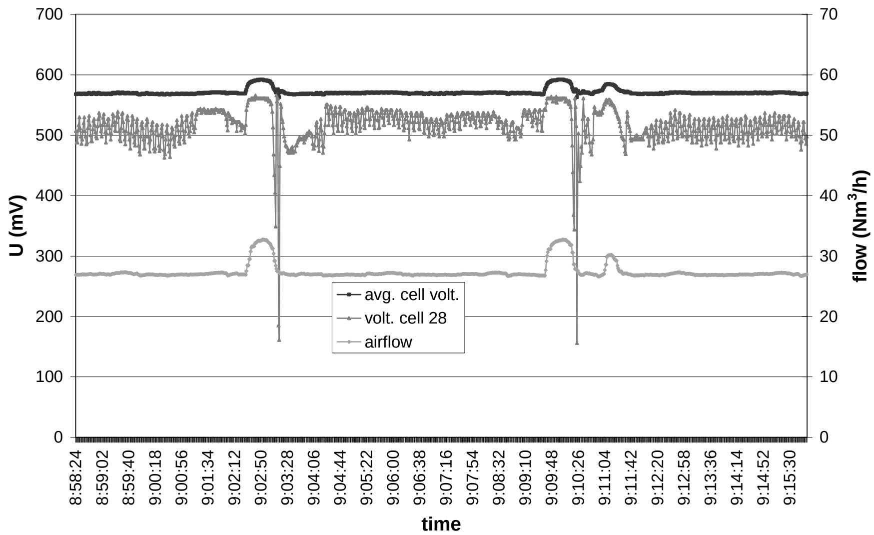

Fig. 4 – Safety issue – A cell with a pinhole can oscillate and suddenly drop in voltage as can been seen in the figure with time series. The average cell voltage, the voltage of cell 28 and the air flow are show. As an automatic control action air flow is increased when cell voltages differ with a certain amount from the average voltage to recover the situation. This happens twice in the figure. However, cell 28 reacts with a sudden voltage drop. This drop is due to a pinhole as was guessed initially and determined after the experiment by opening the stack and examining cell 28.

As is already mentioned, many failures and error situations can be detected by individual cell voltage measurement. A real example is a cell with a pinhole, leading to the crossover of hydrogen or air. Such a cell can oscillate in voltage and suddenly drop, as depicted in Fig. 4. The voltage drop will harm the cell. If one cell fails definitely in a stack, the total stack cannot be used anymore, while the failed cell will go into reversal leading to dangerous electrolysis.

5. Control

Differences in individual cell voltages can have many causes: impurities in the stack, water droplets in gas channels, unequal gas flow through different cells, too dry or too wet membranes, poor electrical contact, damage or degradation of the membrane electrode assembly (MEA), flow fields, etc. In on-site fuel cell systems it is necessary to detect these voltage differences and to remediate the fuel cell stack on-site by adjusting the control of the fuel cell stack, e.g., increasing gas flows, a short purging, or in still worse cases, changing the load for a short time.

For control, data about minimum, maximum and average cell voltage is sent to the main controller of the fuel cell system. On the monitor a transistor output is implemented to give the opportunity to trigger a control action such as short hydrogen purging.

The aspects that we find essential for the control of a fuel cell stack are given in the next paragraphs, backed up by specific measurement results:

(i) multiplexing; it is used in most voltages scanning equipment. It means that all cell voltages are subsequently led to one AD converter. However, it can lead to wrong or unnecessary control actions.

(ii) voltage accuracy; it should be considered why a high or low accuracy is applied.

(iii) cell voltage differences; why do they occur and what to do.

(iv) extra sensors; how can they add to the control function.

(v) scan rate; fast measurement is important in relation to the responsiveness of PEM fuel cells.

All laboratory multi-channel meters (named DMM) are based on multiplexing. This means that one channel at a time is switched to the AD-converter. This leads to errors in transient and dynamic signals: if the electric load is suddenly increased, it is possible that two third of the cell voltages will be still ‘high’ and only one third are at the correct value. For refined control strategies, e.g. gas purging in case of cell voltage deviation, this leads to unnecessary corrections. To overcome this problem, the cell voltage monitor has no central multiplexer and measures all cells quasi simultaneously within less than 0.5 ms. This is enabled by the presence of a single AD-converter for every four consecutive cells, appropriate signal filtering, and over-sampling.

For the examples used in this paper a detection of 100 mV is sufficient, with a control action only required when cell voltage levels diverge by this amount. This results in a need for 10 mV accuracy, since in this way a measured 100 mV difference between cells will lie in between 80 and 120 mV in reality. In the same way an accuracy of 20 mV results in a 60 to 140 mV interval. The low end would lead to too many control actions, lowering the system efficiency. This is the reason that we find an accuracy of 10 mV necessary for our voltage monitoring system.

Internal divergences between cell voltages have several causes as described at the beginning of the section. A cell voltage can steadily lower due to the build-up of water droplets. In this case a control strategy of e.g., gas purging when cell voltages deviate too much, may rectify the situation as depicted by Fig. 5. The control strategy can be implemented into the fuel cell system controller or be provided by the cell voltage monitor with help of the transistor output.

The scan rate is important to follow dynamic electric load environments such as in vehicles. A high scan rate can also be used to analyse the fuel cell response on an intentionally induced electric load variation. With a scan rate of 1000 cells/s in order that e.g. a 100 cell stack can be scanned 10 times/s, the load variations can give interesting information on the state of the fuel cell.

6. Long-term evaluation

Time is a critical parameter for fuel cell stacks. They endure a continuous degradation accelerated by specific events. The ability to store the history of each individual cell together with stack conditions such as the electrical current delivered and the actual working temperature opens a realm of analysis possibilities for the stack developer and system integrator. It leads to insights into reversible and irreversible degradation, and it can be used to remedy off-spec behaviour. Typically, precise long-term data-acquisition is only performed in the laboratory, notwithstanding that most of the problems arise in field applications.

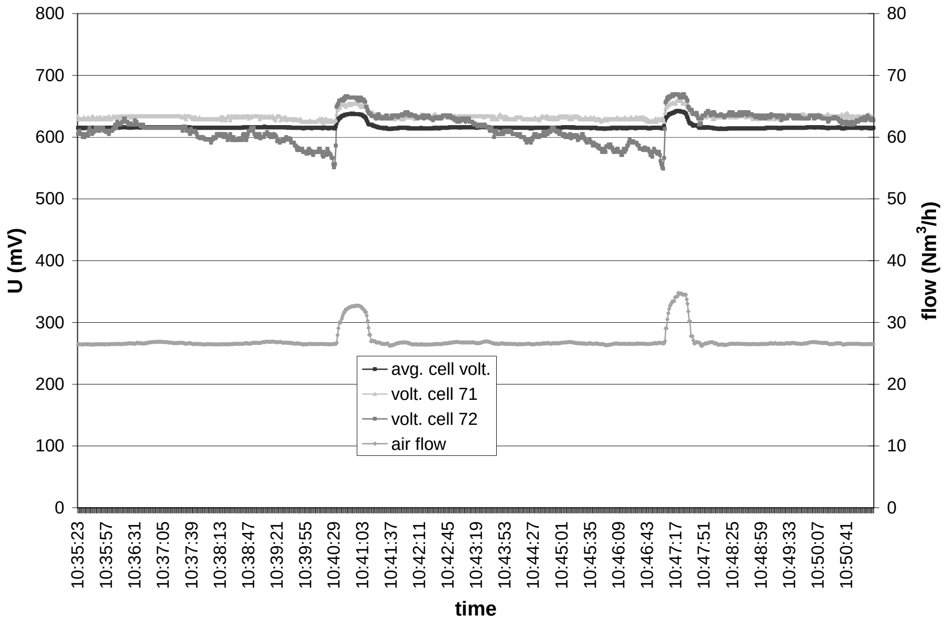

Fig. 5 – Control issue –The time series shows the effectiveness of a gas purge strategy for evacuating water droplets or correcting other gas flow imbalances. It is seen that the voltage of cell 72 decreases steadily. By increasing the air flow rate (represented by the lowest line), the voltage is corrected.

For long-term evaluation the monitor can send all individual cell voltage information to the fuel cell system controller, in addition to the minimum, maximum and average cell voltage that it always sends. The monitor can also store this information itself for later use.

The aspects that we find essential for the control of a fuel cell stack are given in the next paragraphs backed up by measurement results:

- (i) operating hours; these are basic indicators of stack use.
- (ii) voltage accuracy; it is important for detecting gradual degradation.
- (iii) amount of data; this is essential for the ability to store data.
- (iv) extra sensors; they can help with the interpretation of stack behaviour.

A basic indicator for stack operation is the hour counters. Two counters have been included to measure stack operation hours and stack hours at open circuit voltage. The latter is important for catalyst degradation and has to be as short as possible.

Conversion accuracy is excellent for laboratory multi-meters. For fuel cell application, it is better than 1 mV. The monitor has an accuracy of 10 mV and a resolution of 2.5 mV. The latter is possible by using an over-sampling technique. The resolution determines how well a cell degradation can be followed (while the accuracy determines how well cells mutually can be compared). This resolution is sufficient to follow cell degradation as is shown in Fig. 7a. The monitor measures from -0.1 to 1.1 V. In this way, it is possible to know afterwards, when examining the cell voltages, that a cell went into inversion.

For long-term evaluation, resolution and data storage is essential. Depending on the scan rate and the number of cells, the raw data can amount to 45 MB/ day (in ASCII format). For long-term evaluation, with no large hard disk available, data compression becomes imperative. We integrated a no-data-loss algorithm. The typical data of one day was compressed 15 times resulting in 3 MB/day and then written to a SD memory card. This will enable a year of data to be stored on a 1 GB memory card.

The monitor has three 0–5 V inputs for other information than cell voltage levels. This makes a more precise long-term evaluation possible while e.g., it can be derived to which current the cell voltage levels correspond, distinguishing a degradation effect from slow electric load variation, as shown in Fig. 7.

We can conclude that precise long-term data-acquisition is interesting for on-site fuel cell stacks, particularly as on-site stacks operate longer than laboratory stacks and undergo more often off-spec situations. While conventional measurement equipment is too expensive and lacking robustness, and there is usually no data acquisition computer nearby, we implemented specific features in the monitor for its long-term evaluation goal.

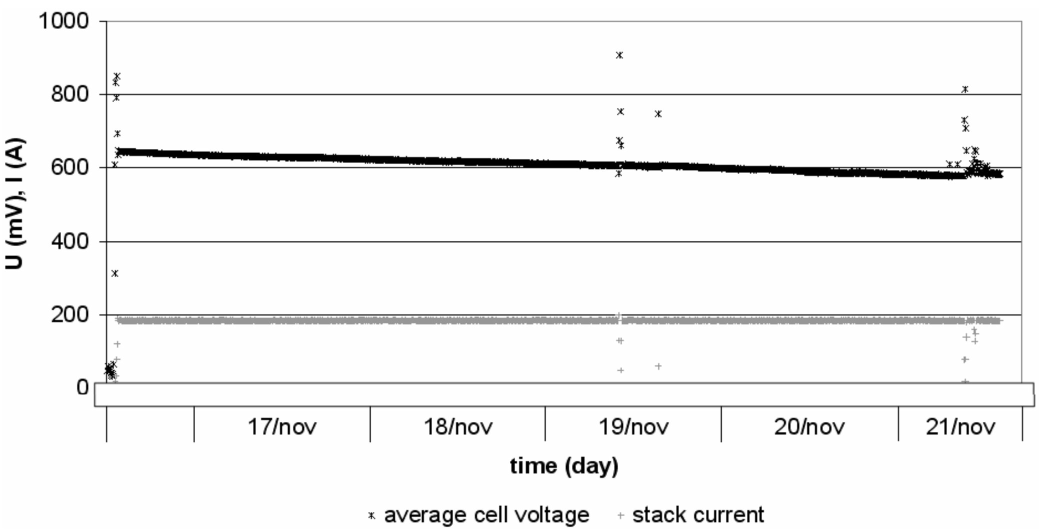

Fig. 7 – Long-term evaluation – Example of stack degradation against time.

7. Comparison of communication protocols

A comparison is carried out for the communication rate towards a main controller for two types of data transmission, CAN and RS232. The experiment shows the superiority of the CAN-bus.

To test the communication rate a 0.1 Hz sine-wave is examined. The laboratory device of the previous paragraph has an output by GPIB allowing a data transmission rate of 1 MB/s. However, due to the multiplexing method it takes 2 s to scan 80 cell voltages. This leaves 5 points to represent the sine wave, which is too few for this signal. The monitor scans about 100 points of the sine wave period. However, this does not mean that these measurement data points arrive at the fuel cell system controller. This depends on the communication protocol as is revealed in the next paragraph.

The monitor is equipped with the possibility to retransmit data by RS232 and CAN. RS232 is a serial, non-deterministic communication method available on most computers and micro-controllers, while CAN is a network deterministic protocol. To reveal the difference in behaviour, the 0.1 Hz sine-wave was imposed and the result was transmitted over RS232 and CAN. To read and present the data, Labview 7.1, the serial connector of the computer (for RS232) and a CAN-card (National Instruments) has been used. Fig. 8a shows that the sine-wave is deformed by the RS232 due to the non-deterministic communication. The CAN transmission allows much faster acquisition rates leading to a pure sine-signal (Fig. 8b). The visible variations here are due to the voltage input resolution of the cell voltage monitor.

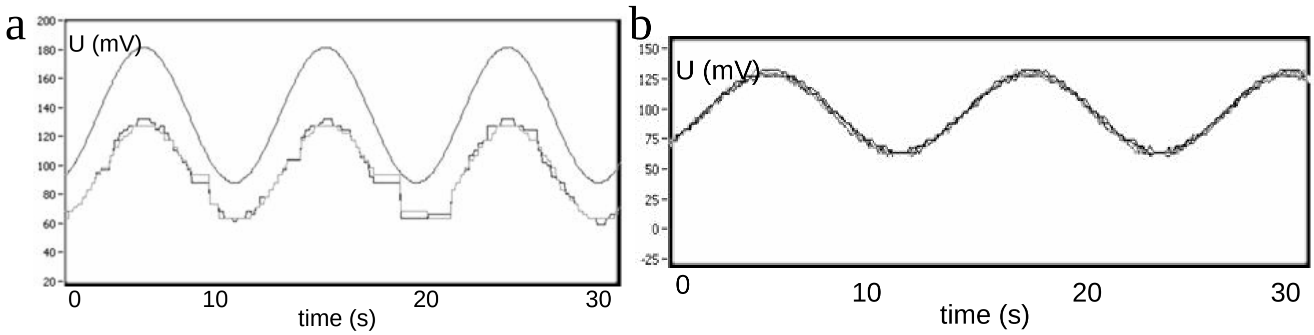

Fig. 8 – Data-transmission of a 0.1 Hz sine waveform by two different methods. (a) By serial RS232. (b) By the CAN, shown for 4 cells. Both figures are screen-dumps during the actual measurement.

8. Conclusions

Cell voltage monitoring is at present the best applicable detection method for on-site stacks. In this article it has been shown that a real effort has to be made to obtain a dedicated on-site monitor in comparison with laboratory equipment.

In relation to safety issues cell voltage monitoring is an essential element for on-site fuel cell stack operation: many failure situations lead to a drop in cell voltage. On top of that, low cell voltage detection is the predominant cause of stack shutdown. Our cell voltage monitor has a good voltage range and an adequate scan rate for this aim. Examples showed its adequacy.

Using a cell voltage monitor is advantageous for fuel cell control in terms of efficiency and a balanced situation within the stack. Cell voltage monitoring leads to optimised control resulting into improved reliability and lower operational costs.

Precise long-term data-acquisition is interesting for on-site fuel cell stacks, particularly as on-site stacks operate longer than laboratory stacks and undergo more often off-spec situations. It generates the necessary feed-back for the research team on incidental events and stack degradation.

The cell voltage monitor described here is robust and dedicated for on-site application. Due to the additional sensor inputs and actuator outputs it can take over part of the FC management. This is particularly beneficial for modularisation in multi-stack arrangement (see Fig. 9).

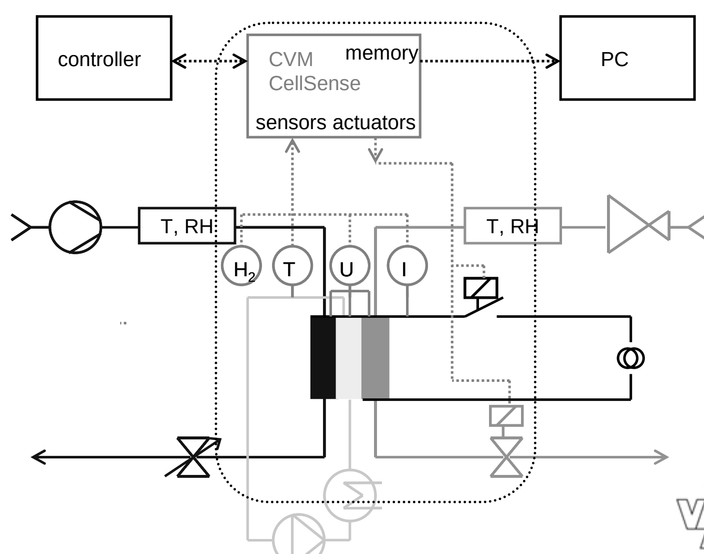

Fig. 9 – Our cell voltage monitor and its role within FC management