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Online Fuel Cell Monitoring and Operating Conditions Identification Including Life Time Measurement

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Abstract: An advanced version, AVL THDA, was developed to monitor the proton exchange membrane fuel cell (PEMFC) without using single cell voltage measurement (CVM) fault diagnosis and evaluate State of Health (SOH). The AVL THDA detects critical voltage drifts on cell level to ensure reliable operating conditions using harmonic distortion and electrical impedance spectroscopy. Detected critical operating conditions are assessed online and classified into membrane dry-out, liquid water droplets and low media supply issues. Thus, a system controller can immediately initiate counter measures preventing stack degradation. Taking into account long term effects in the fuel cell, also life time estimation is considered. The technology is capable of being fully integrated into existing fuel cell system components, therefore, has potential of cost efficient application.

Key words: fuel cell (FC) monitoring; proton exchange membrane fuel cell (PEMFC); life time measurement; online diagnostics; harmonic distortion; electrical impedance spectroscopy

包含寿命监测的在线燃料电池监测和运行状态识别

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摘　要: 为故障诊断和健康度(SOH)估计，开发了一种不使用单一电池电压测量(CVM)的质子交换膜燃料电池(PEMFC)的监测技术——“AVL THDA”。该技术运用谐波偏移、电抗谱技术，监测电池组的临界电压迁移，以保证可靠的运行状态；运行状态被在线评估，并被分成膜干涸、液体水滴和介质供应不足等几类。电池系统控制器可以立即启动计数测量，以防止电池的退化；考虑到了对于电池的长期影响，以及生命周期评估。该技术可以被集成到现有的燃料电池系统构件中，因此具有经济应用的前景。

关键词: 燃料电池(FC)检测；质子交换膜燃料电池(PEMFC)；生命周期测量；在线诊断；谐波偏移；电抗谱

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Introduction

The motivation for the development of an alternative fuel cell (FC) monitoring technology was to generate an expert system combining different electrical instrumentation principles into one comprehensive unit but still remaining on a minimum of hardware effort.

The main function of such a monitoring system is seen in the reliable detection and determination of critical conditions in stacks allowing the right counteraction against degradation mechanism. This functionality must ensure robustness over the whole life time cycle. Since stack characteristics change over life time an online algorithm to determine the current state of health has to be implemented.

An important boundary condition in proton exchange membrane fuel cell (PEMFC) systems is the cost. Sensors, wires and other hardware components should be reduced to a minimum or rather fully eliminated.

1 Background Information

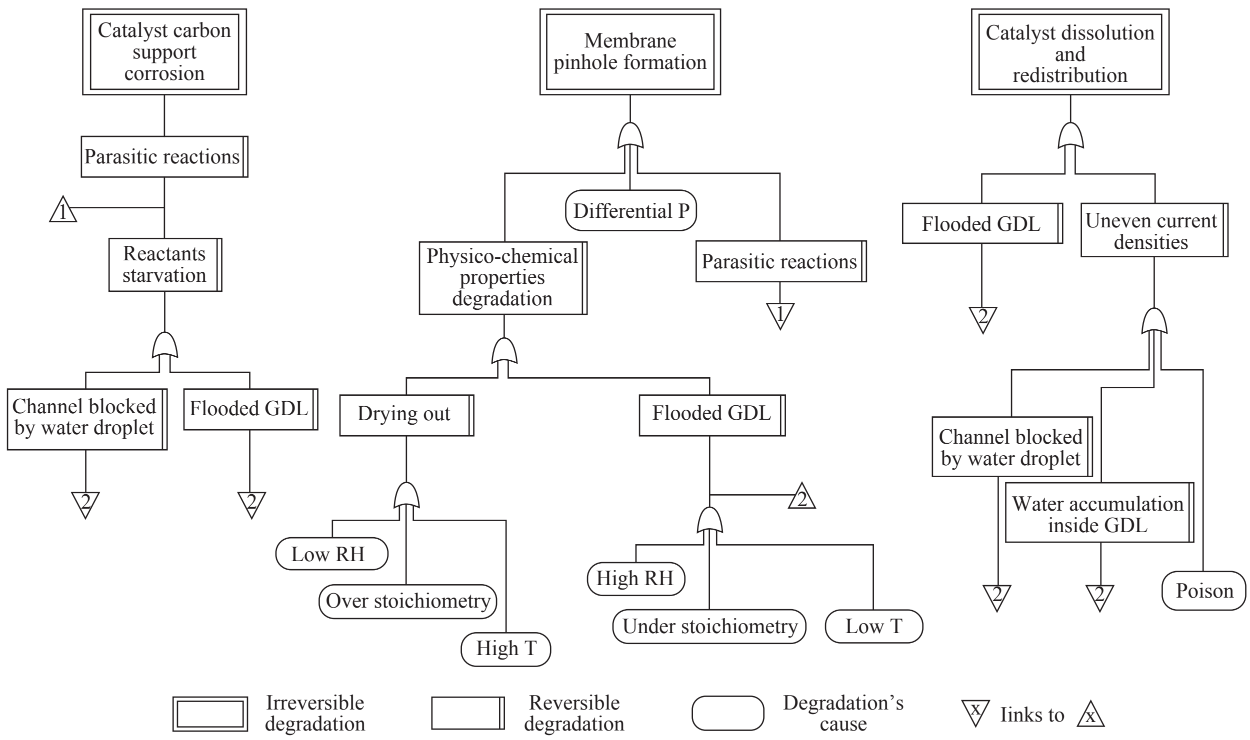
The companies AVL and PSA initiated together with the Technical University of Graz (TUG) a cooperative project. Over the past few years, different approaches have been investigated at AVL [1-2], PSA [2-3] and TUG [3-4] in order to address the challenge of PEMFC state of health monitoring. Each of these approaches has the same scientific background, namely the online analysis of the frequency response of fuel cells and the correlation to their states of health.

The current project approach combines the different partner experiences and specifically the university contributes to the scientific aspect, AVL with its experience in PEMFC instrumentation technologies ("AVL THDA ™" , see [1]) and the car manufacturer PSA completes the project with the view from an OEM for practical application.

1.1 PEMFC Degradation Mechanism

PEMFC' s membrane electrode assembly limited durability is an important scientific and technical challenge for large scale introduction of this technology. At least 3 000 to 5 000 operational hours are required for automotive applications, up to 2×10^4 h for heavy duty trucks and up to 4×10^4 h for stationary applications. A maximum rate of degradation ranging from 2 to 10 μV/h is sought for the majority of the applications, which amounts to an end of life power loss below 10%.

As shown in Figure 1and reported in several studies [5-16] water management plays a fundamental role on the path towards irreversible degradation of the membrane electrode assembly's (MEA) performances. Ensuring constant and optimal water content within MEA is thus a major challenge in fuel cell system command and control. Consequently it is chosen to focus the diagnosis work of the diagnosis technology to water issues.



T—temptrature; P—pressure; RH—relatiue humidity; GDL—gasdiffusion tayer

Fig. 1 Fault Tree

1.2 AVL THDA

AVL has been developing a patented stack monitoring technology "AVL THDA ™" which serves as basic approach.

This technology is based on measurement of the effects of voltage drops instead of direct measurement of voltage drops[1-2]. The approach is based on the superimposition of a small amplitude current signal onto the stack followed by analysis of the system response (i.e. the stack voltage) in terms of harmonic distortion.

As long as the cells are well operating, the specific cell transfer function is locally linear and the responding voltage signal-shape does not differ from the superimposed current signal. In case of critical cell operation (i.e. during cell voltage drops) the stack transfer function is locally non-linear and the corresponding voltage signal becomes harmonically distorted i.e. extra spectral components are formed. The existence of spectral components in the (voltage-) signal is used for indication of critical stack conditions. With the appropriate preconditions the sensitivity is high enough to detect harmonics even if they are generated by only one single ill working cell in a stack. For that reason THDA is a two channel approach and cell voltage measurement is not needed.

The THDA hardware consists in principle of two blocks (Fig. 2). An amplifier superimposes an analog alternating current signal pattern to the stack. The signal pattern is calculated by a microprocessor. A capacitor excludes the amplifier from high stack voltages and let pass alternating signals only. In a second block the two signals stack voltage and stack current are filtered, sampled and converted to digital data. The signals are further processed in the frequency domain.

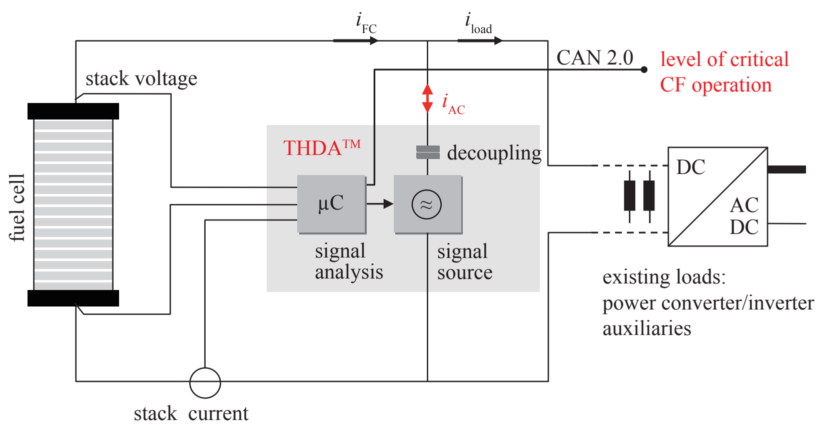


Fig. 2 Hardware Approach

Under practical automotive conditions the frequency range where stack parameters can be extracted reliably is between 8 Hz and 500 Hz. Signals at lower frequencies are mostly impacted and overlaid by transient load changes and above 500 Hz inductive impacts depending on wiring and its geometry are dominant.

It was therefore decided to focus all fuel cell monitoring algorithm to the above mentioned frequency range.

1.3 Impedance Measurement

With time the physical-chemical properties of the membrane electrodes assemblies change. If this is not taken into account, there will be no way to distinguish between a change of parameters that would be due to a change in the MEA's water content and one that is due to ageing.

An example how low air supply condition influences the impedance characteristic of a stack is shown in Fig. 3. The 3D surface is the real and imaginary fraction of the stack impedance over life cycle. The horizontal vectors show the impact of lower air supply.

Hence, without further investigation, the interpretation of measured impedance parameters is not really feasible.

Further, it must be considered that measurements during insufficient fuel or air supply cause time variant conditions in the cell i.e. the possible time frame for a full impedance

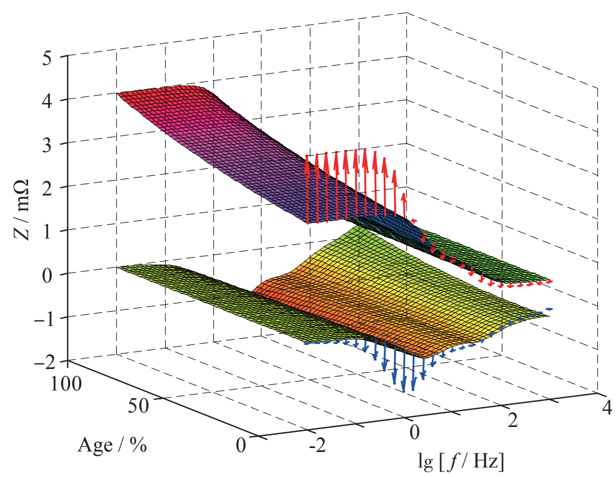


Fig. 3 Real and Imaginary Stack Impedance over Full Life Time Cycle and Impact of Low Media Supply (Vectors)

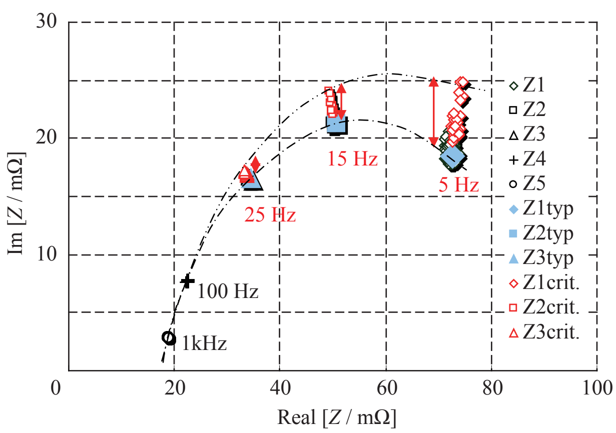
scan is very short. Standard procedures apply a point by point impedance measurement over a certain frequency range. This means that the different data points of an impedance curve relate to different points of time. Typically time variant conditions on a stack form harmonics and generate failures in the impedance measurement.

Hence, standard impedance measurement procedures are neither practicable for online monitoring nor for state of health measurement. Special fast impedance spectroscopy approaches are therefore applied in the extended THDA method. The implemented online impedance measurement function outputs full impedance curves two times per second. It is ensured that the impedances refer at each frequency to the same point in time (i.e. transient conditions are measured correct).

Figure 4 shows the online Nyquist plot of a stack during varying air supply conditions measured with THDA approach. The labels "Z1" to "Z5" in this figure represent the online measured complex impedance values at five different frequencies; the labels "Z1typ" to "Z5typ" indicate uncritical air supply conditions whereas "Z1crit" to "Z5crit" shows the results during varying air supply conditions. It can be concluded that in this case only the imaginary fraction at low frequencies changes i.e. the Ohmic activation resistance of the cathode is impacted whereupon the double layer capacity remains unchanged.

2 Comprehensive Fuel Cell Monitoring

The technical approach is structured into three complementary principles but only one common instrumentation method, namely the superimposition of small alternating current signals to the stack and analysis of the signal responses from the stack (i.e. THDA principle, ref. to Section 1.2 and Fig. 5, in Fig. 5,



air lambda varies from 2.1 to 1.6; frequencies=6/14/26/96/1 000 Hz
AVL List GmbH

"Z1" to "Z5" —at different frequencies;
"Z1typ" to "Z5typ" —at uncritical air supply conditions;
"Z1crit" to "Z5crit" — during varying air supply conditions.

Fig. 4 Nyquist Plot with THDA during Time Variant Conditions in a PEMFC Stack

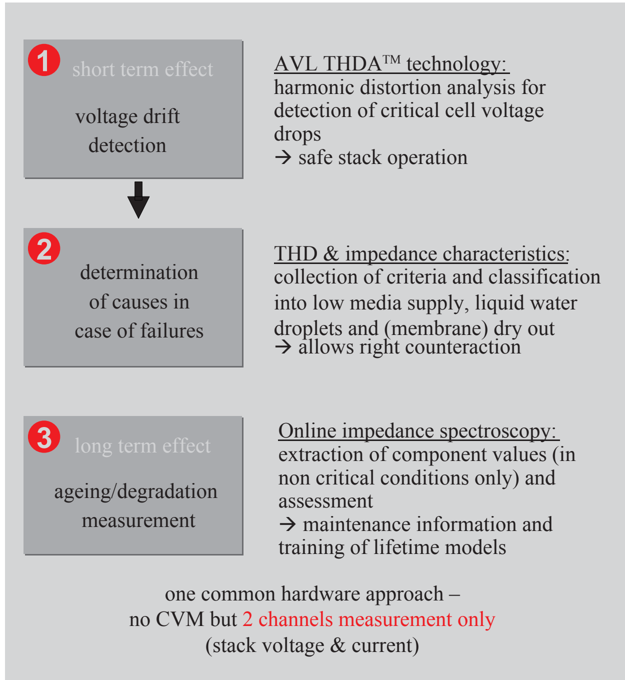


Fig. 5 Principle Approach

CVM means Cell Voltage Monitoring).

2.1 Cell Voltage Drop Detection

The first stage in the monitoring approach is the detection of critical drops of cell voltages in a stack without single cell voltage measurement on basis of the harmonic distortion analysis technology "THDA" (Section 1.2, [1]). An online signal output is generated and indicates in case of critical cell conditions the corresponding information.

The basic function of this block is to ensure safe stack operation in general.

2.2 Determination of Failure Causes

The identification of reasons for the detected critical conditions is the sophisticated interpretation of the correlation between collected electrical parameters and its typical characteristics during exceptional operating. Three additional output signals are online calculated:

- intensity of liquid water droplets
- intensity of dry-out (membrane)
- intensity of low media supply

Fuel cell stacks react differently under these various critical operating conditions. For example, liquid water droplets in flow field channels cause spontaneous, sharp and random voltage drops. At the same time this can be seen as blocking of the media supply i.e. fuel starvation on the electrode. The deciding difference is that liquid water is a random and transient event whereupon fuel starvation gives less spontaneous changes in signal characteristics. This circumstance – different conditions form different and specific signal characteristics – is used for determination of reasons of detected critical conditions in a fuel cell [2].

A practical example during (user enforced) membrane dry-out condition measured in PSA's fully equipped PEM fuel cell system is shown in Fig. 6. Output "THDA_dryout" shows a critical increase whereupon the two other outputs for low media supply and liquid water droplets remain at low level.

Another example how THDA distinguish between liquid water droplets and low media (air) supply is shown in Fig. 7. In this test the formation of liquid water droplets was enforced by reducing the air supply of the stack. Output "THDA_liquid" indicates the very short but sharp events of blocking water droplets in the flowfield during operation under lowered air supply ("THDA_lowMedia"). The formation of liquid water droplets disappeared rather slowly after returning to standard conditions.

The test with lowered hydrogen concentration on anode side has neither shown interrelations to water formation nor to membrane dry-out effects (Fig. 8).

Figures 6 to 8 refer to measurements on a small size, fully equipped PSA PEMFC system build around a 100 cells stack. The stack powers the system auxiliary components directly. It means that THDA output channels are already compensated against electro-magnetic interferences or noise impacts. Every test was manually supervised ensuring that the weakest cell

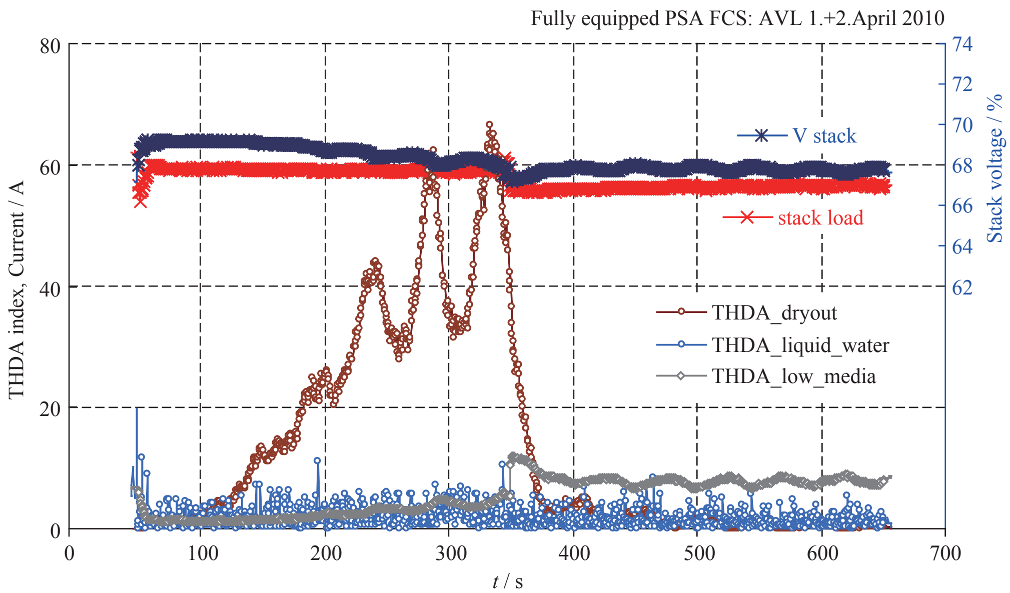


Fig. 6 THDA Outputs During

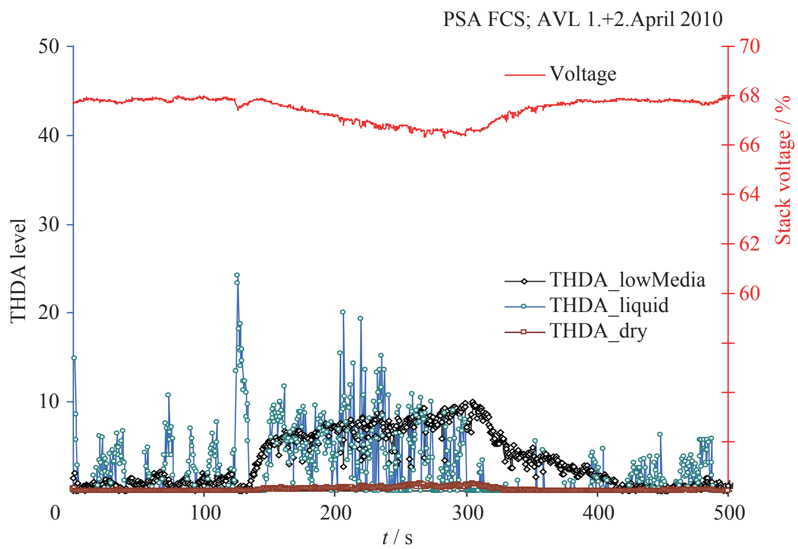


Fig. 7 THDA Outputs during Enforced Formation of Liquid Water Droplets

voltage (measured with a Cell Voltage Monitoring system) remained all time above the lowest allowed voltage level.

2.3 State of Health Measurement

State of health information is basically derived from the measurement of electrical stack impedances at certain frequencies in parallel, and its long term variations.

The challenge is that under practical automotive conditions the lowest applicable frequency showing reliable results is approx. 8 Hz, but the correlation between aging and impedance increase (Fig. 9) is much higher at lower frequencies.

The THDA device in the impedance scan mode (Fig.4) provides online and continuously phase and magnitude parameters over the specified frequency range. A standard electro-equivalent circuit was selected and serves as algorithm for the interpolation of the entire impedance curve. On basis

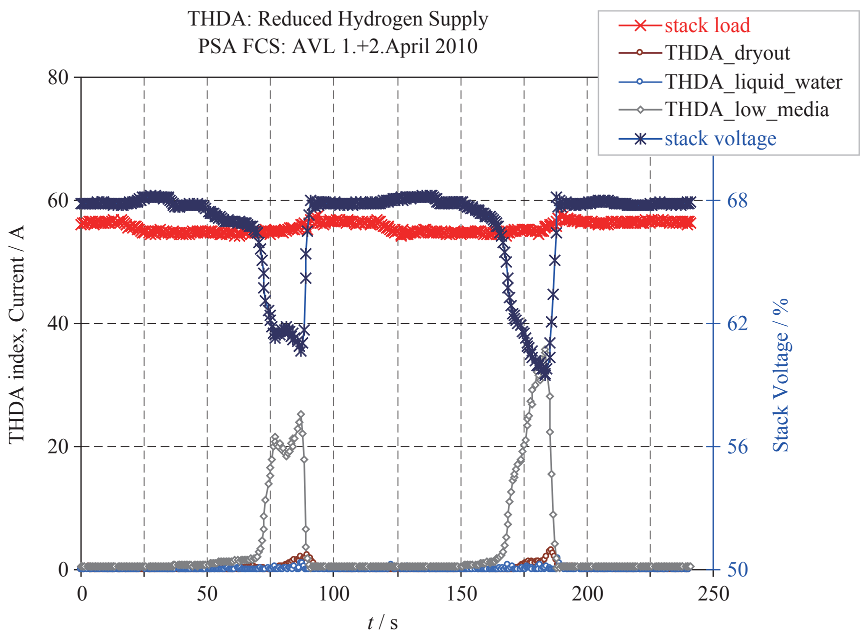


Fig. 8 THDA Outputs during Reduced Hydrogen Supply

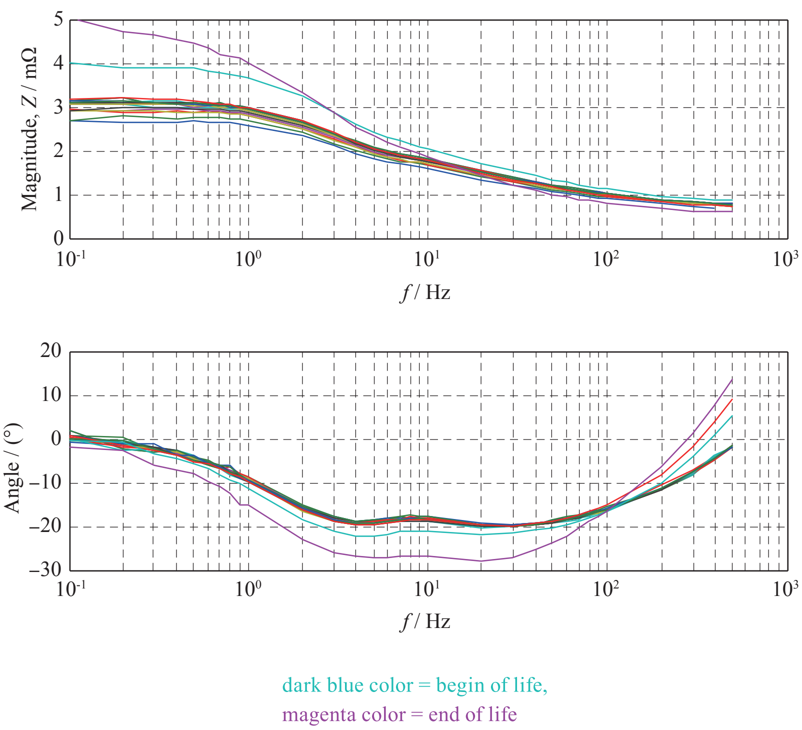


Fig. 9 Bode Diagram for the Entire Life Cycle

of mathematical calculations the coefficients are extracted and assessed in terms of changes. As shown on Figure 10 not all of the generalized and normalized coefficients are useable for state of health calculation. The eliminating criteria are a) importance at low frequencies only, b) high sensitivity to varying operating conditions and c) less or no correlation to life time. Finally the two coefficients labeled with “A1” and “B1” has shown good sensitivity (-50% absolute change over life time) and relevance at the frequency area above 8Hz.

As in section 1.3 described impedance results are significantly impacted by critical or varying fuel cell operating conditions.

With extended THDA functionality the fuel cell status is continuously known and improves consequently the accuracy of state of health measurement. In case critical conditions like liquid water droplets or media supply issues were detected the state of health measurement is temporarily suppressed.

3 Aspects for Practical Application

For series application the hardware approach as shown in Fig. 2 can be minimized through fully integration of the functions into existing fuel cell system components.

For superimposition of alternating current signals the power converter/inverter can be modified in the following two ways: a) low power bypass circuit in parallel to the main load control or b) direct addition of the small signal pattern to the main load applicable at high dynamic power converters/inverters. The signal magnitude is in the range of few amperes and does not consume effective power from the stack.

Apart from data acquisition and filtering the signal analysis is

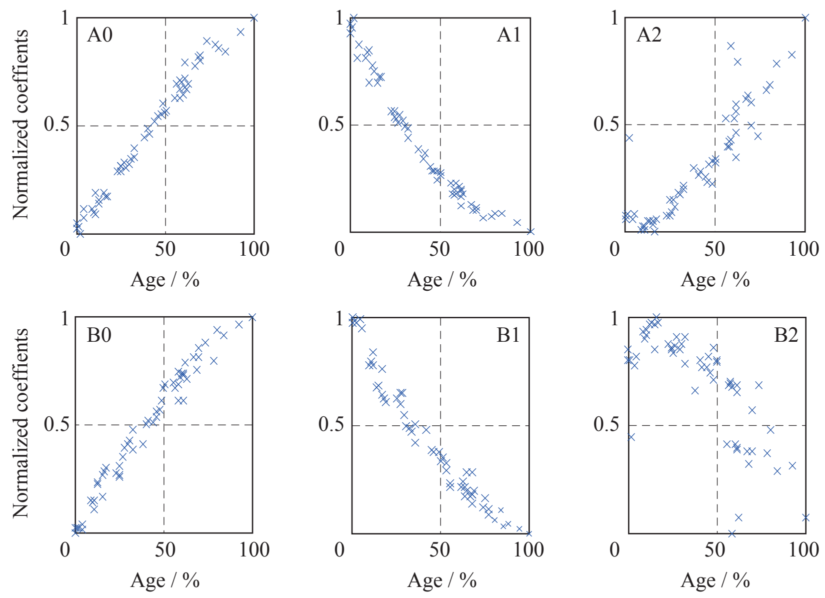


Fig. 10 Correlation of Normalized and Generalized Coefficients in Percent to Stack Age

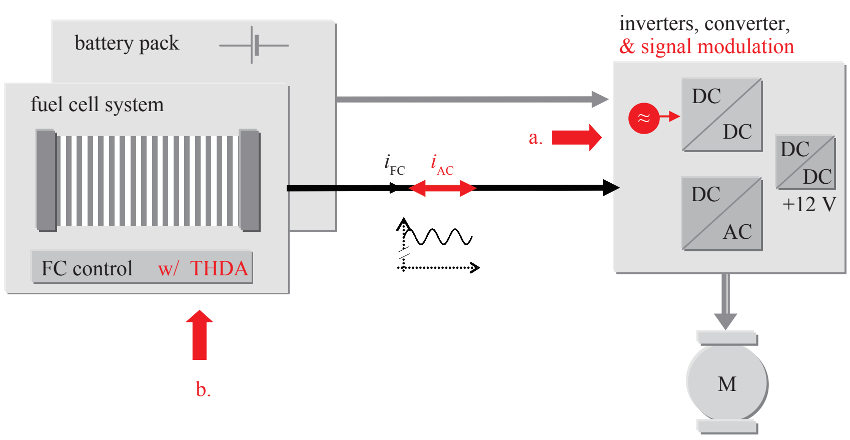


Fig. 11 Fully Integrated Solution

a pure software module and can be embedded directly into the electronic control unit of the fuel cell system (Fig. 11, label "b."). The stack current is already available in the fuel cell controller and the hall sensor can be also eliminated.

Thus the entire monitoring technology is capable of being fully implemented into existing components and has therefore good potential for lowering fuel cell system costs.

4 Summary

The described approach allows comprehensive monitoring of PEM fuel cell systems for detection of critical conditions on cell level (without CVM), determination of failure causes and state of health measurement.

The provided output information supports fuel cell controllers to counteract efficiently in case of critical conditions.

All functions are optimized for application under transient automotive operating conditions and developed for robustness against electrical interferences or noise impacts.

The hardware effort is reduced to the measurement of only two signals: stack voltage and current. For series application the entire functionality can be integrated into existing fuel cell components i.e. cost effectiveness is given.

Acknowledgement

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