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Short communication

Detection of fuel cell critical status by stack voltage analysis

Erich Ramschak[a,*], Volker Peinecke[a], Peter Prenninger[a], Thomas Schaffer[b], Viktor Hacker[b]

[a] *AVL List GmbH, Hans-List-Platz 1, 8020 Graz, Austria*
[b] *Graz University of Technology, Institute for Chemistry and Technology of Inorganic Materials, CD-Laboratory for Fuel Cell Systems, Steyrergasse 21, 8010 Graz, Austria*

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Abstract

In comparison to state of the art fuel cell stack monitoring techniques, where for reliability and durability reasons either single cell or cell-block voltages are monitored separately, the new approach derives information about critical cell and stack status from the stack sum voltage only. The motivation for the development of such a technology is to establish a strongly simplified and low cost stack diagnosis unit. In comparison to the cell voltage monitoring (CVM) technology, where up to several hundreds voltage channels have to be measured separately or at least in pairs, the effort for wiring, contacting and instrumentation can be reduced dramatically.

Critical cell operation occurs, if e.g. low air stoichiometry causes a sharp drop of voltage at a certain cell current. If in such case the current is superimposed by a small amplitude signal with specific frequency pattern, then the system response (i.e. stack voltage) will be distorted in the frequency domain. Particularly, this means that even if only one single cell is in a critical operation mode, it would cause distorted frequency fractions extractable from the entire stack voltage. Since this approach is related to the distortion of the frequency pattern only, noise and EMC issues are not significantly influencing the measuring quality. The instrumentation and processing effort is rather low and can be realized with a low cost DSP board.

Measurement results for different critical stack operation modes, e.g. operation at low air or low hydrogen stoichiometry, with their correlation to the frequency distortion will be described and discussed.

Keywords: Frequency distortion; Distortion analysis; Critical stack monitoring; Spectral analysis

1. Introduction

The serial connection of several cells in a stack implies the potential danger, that critical operation of even just a single cell can cause the failure of the whole stack and thus shorten lifetime ore reduce the reliability. The possible failure of a cell is usually monitored by measuring all voltages of every single cell or every cell pair. The wiring and also instrumentation effort at large fuel cell stacks is therefore costly and complicated.

Hence, the requirement is to establish a strongly simplified and low cost stack monitoring technology primary feasible for systems with large production volumes. The operating status should be derived from the stack sum voltage only. An output signal should be provided real-time indicating whether the stack or rather every single cell operates under safe and reliable conditions.

2. Harmonic distortion analysis approach

In case of critical cell operation caused by e.g. insufficient air supply, the cell transfer function becomes non-linear and causes therefore harmonic distortion of a signal. This distortion forms harmonics at integer orders of the fundamental frequency of the signal.

At the new approach, during fuel cell operation, thus in parallel to the fuel cell operating point, a small amplitude sinusoidal current signal is superimposed continuously to the stack current. As long as the cell transfer function (i.e. *V*/*I* curve) is linear,

* Corresponding author. Tel.: +43 316 787 3784; fax: +43 316 787 3799.
E-mail addresses: erich.ramschak@avl.com (E. Ramschak), volker.peinecke@avl.com (V. Peinecke), peter.prenninger@avl.com (P. Prenninger).

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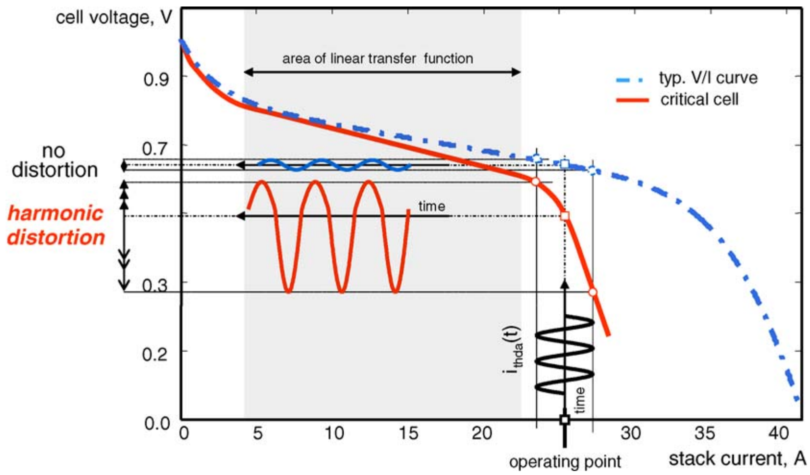

Fig. 1. Distortion of a sinusoidal signal (principle).

which is the case within the usual operation range, the responding cell voltage signal consist of the same frequency spectrum as the original superimposed one.

Formed harmonics, caused by critical operating conditions, were detected in the frequency spectrum of the entire stack voltage, even if only one or few cells generate harmonic distortion and therefore extra spectral contents.

The spectral content of the measured (voltage-) signal is correlated to the spectral content of the superimposed (current-) signals. Deviations are analyzed and evaluated in terms of critical fuel cell status.

Since this new approach analyses the formation of harmonic distortion, the acronym "THDA" (total harmonic distortion analysis) is used for this technology.

Fig. 1 shows in principle the distortion of a sinusoidal current signal if an actual operating current is either at a critical (solid curve) or at a typical normal (dashed–doted curve) condition. Generally, harmonic distortion occurs at conditions with insufficient air or hydrogen supply at mass transport limitations or even during cell voltage drifts or temporarily drops caused by other reasons.

2.1. Principle hardware realization of THDA

In Fig. 2, the hardware setup is described schematically. An auxiliary signal source is adding a small amplitude alternating current (AC) signal to the system. With a capacitor this AC signal is shifted to the usually high DC (direct current) level of the stack voltage. On average, the stack output power is not influenced by this device. The stack is loaded and unloaded adequately to the superimposed current (rule of Kirchhoff, refer to Fig. 2: $I_{STACK} = I_{LOAD} - I_{THDA}$). The sinks for the AC signal are the external loads and system auxiliaries.

At stationary fuel cell systems, only the measurement of the sum voltage of up to several hundreds cells is required. At transient loaded systems, the additional measurement of the current is needed in order to compensate the spectral impact of sharp load changes. Only the AC part of the stack voltage is measured (high pass coupling) and, thus, the full dynamic range of the analogue digital converter (ADC) can be utilized for the analysis of the AC signal content.

The measurement, de-noising, transformation of the signals into the time–frequency and frequency domain with the subse-

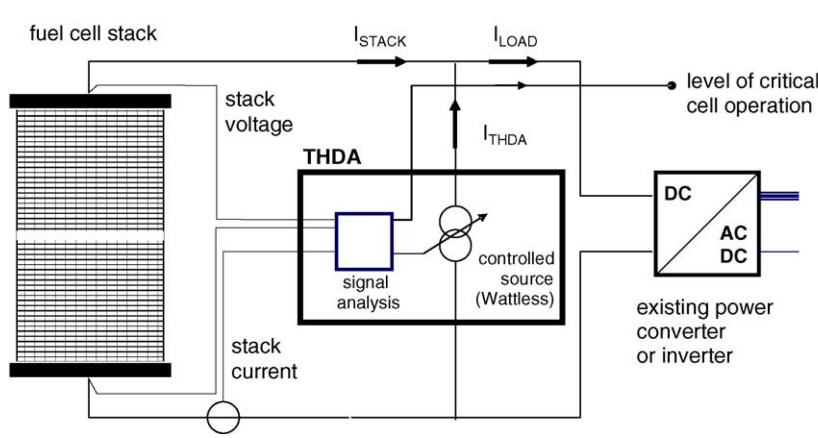

Fig. 2. HW realization of THDA.

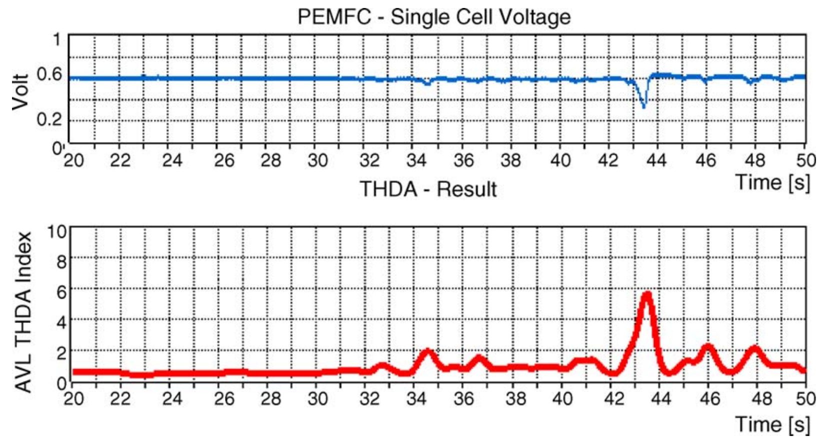

Fig. 3. THDA output for operation at low air stoichiometry.

quent analysis can be established by an embedded digital signal processor (DSP) board with low complexity. The processing time is short enough allowing real-time calculation even at transient operation.

3. Measurement results

First fundamental measurements were carried out with single cells at stationary conditions for a variety of parameters in order to proof, that changes in the stoichiometry of the cathode or anode gases lead to the predicted THDA results.

Fully saturated gases were fed to a single cell with an active area of 25 cm^2. All measurements were performed at constant current density of 600 mA cm^{-2} and at 70 °C operating temperature. The MEA was a commercially available product with an anodize load of 0.4 mg Pt cm^{-2}, the cathode catalyst load was 0.6 mg Pt cm^{-2}. A microporous layer on a carbon paper gas diffusion support was used.

For simulating critical conditions on cathode side, the air stoichiometry was reduced simulating a shortage of air supply for the cathode. At reduced air flow, the partial pressure of the oxygen decreases proportionally and leads to a higher diffusion resistance at the cathode [1]. That effect caused cell voltage drifts and slight drops which formed harmonic distortion of the superimposed signal (Fig. 3). Even small changes of the cell potential could be clearly detected with the THDA technology.

Similar experiments for an anodized gas starvation resulted also in drifting cell voltages due to the bad stoichiometry. In Fig. 4 the anode of the fuel cell was insufficient supplied, i.e. the anodized gas support (from $\lambda = 2$) was slightly decreased until first drops in the cell voltage were detected. Also for this operating mode the applied THDA technology could clearly detect if critical anode conditions occurred.

3.1. Fuel cell system results

When harmonic distortion is formed by just one single cell or few cells under critical operating conditions, the resulting spectral components can be also detected in the frequency spectrum of the entire stack sum voltage. For verification, tests with PEMFC and SOFC full stacks were performed. All single cell voltage levels were also recorded as reference for the assessment of the THDA results.

At the 1 kW PEMFC system, a small amplitude sinusoidal current (1.0 A_{pk}) was superimposed to the transient system current. The supplying air mass flow was limited for equivalent maximum current output of 60 A. At about 63 A, one single cell suffered at first under the limited air supply, and caused already detectable harmonic distortion of the superimposed sinusoidal

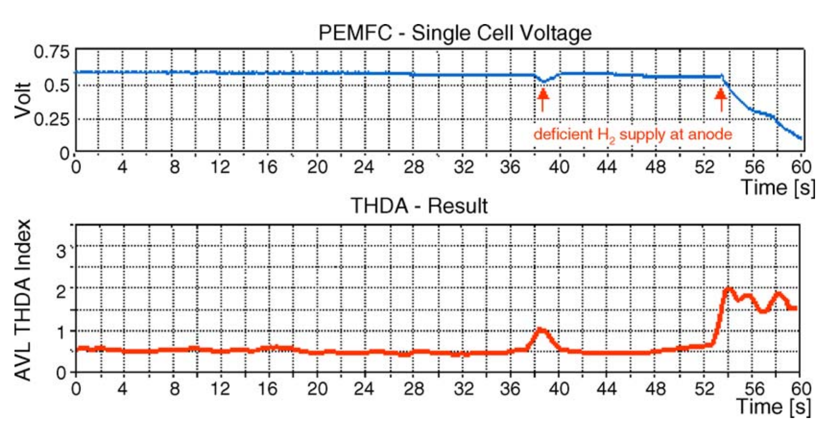

Fig. 4. THDA output for critical conditions on anode.

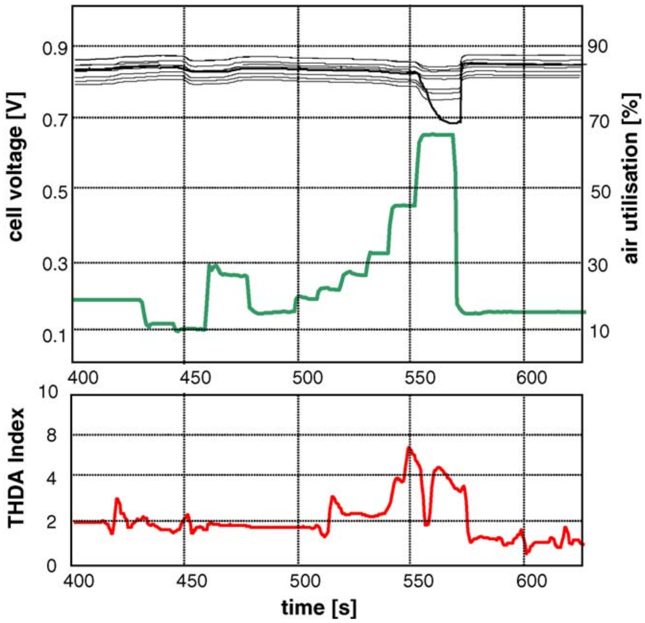

Fig. 5. One kilowatt SOFC system result.

signal. At higher currents, several cells showed drifting or dropping voltage effects, and caused equivalent higher amplitudes of the harmonics.

Further, THDA tests were made under stationary load conditions with a 50-cell SOFC stack. A small amplitude sinusoidal AC current signal (amplitude = approx. 1% of the load) was superimposed to the system current. Since high air utilization values can cause critical cell voltages drifts or in the worst case voltage break downs at some single cells, the air utilization factor was slightly increased (i.e. reduction of air mass flow) until the first cell voltage started to drop to a critical level of about 0.7 V. The result of THDA is shown in Fig. 5. This signal can be used in an external control unit to decide about critical operation of the stack if e.g. a THDA-level of 4 is exceeded. It should be noted that the harmonic distortion analysis according to the THDA approach is achieved by measuring the total stack voltage only.

3.2. Discussion of key challenges for on-line analysis in fuel cell systems

In relation to isolated stack measurements in a lab, the THDA technology has to resist impacts from electrical system components like converters, inverters, switching valves, sharp transient load changes, noise and electromagnetic interferences (EMI) in a real fuel cell system. The influences from transient load changes to the harmonic spectrum of the THDA-signal are detectable as above mentioned and can be compensated therefore.

An advantage of the THDA approach is that the transformation into the frequency domain and also the exact knowledge of only possible spectral components (i.e. integer multiples of the fundamental frequency) significantly reduces EMI impacts. Further, by applying de-noising algorithms (e.g. [2]), which are operating in the time–frequency domain, noise and valve switching impacts are mostly controllable.

The definition of the maximum number of cells in a stack, which can be monitored with the THDA technology, depends on one hand on the capability to separate large from relatively small and narrow spectral components and, on the other hand, on the stack (impedance) characteristics itself. Thus, specifications like resolution of the analogue–digital converter, sample frequency, window length settings for the frequency transformation, required time resolution for the output and stack impedance curve characteristics are the constraints for the calibration process of THDA.

4. Summary

The formation of harmonics can be used for detection of critical cell operating status of PEMFC and SOFC stacks embedded in fuel cell systems. The harmonics can be detected in the frequency spectrum of the entire stack voltage even if only single or few cells generate harmonic distortion of a superimposed signal.

The AVL THDA technology is based on the harmonic distortion analysis of the stack sum voltage for monitoring critical stack operating status. It is applicable during fuel cell operation without the need to change or adapt the actual operating conditions of a fuel cell system. The instrumentation effort is rather small and of relatively low complexity. Hence, also no extra wires at stacks are required.

In comparison to state of the art stack monitoring devices, the THDA technology does not provide new or improved information contents, but it is targeted to lower the cost and complexity of fuel cell systems as well as enables stack diagnosis even if systems are not equipped with single cell wires.

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