Automated Evaluation of Operation of Electrochemical Sensors for Environmental Monitoring

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Abstract- The present paper describes a novel application of a well known Build-In-Self-Test (BIST) method in order to evaluate the operational condition of a certain type of sensors which are widely used in environmental monitoring instruments (especially in water quality monitoring). It is actually an automated evaluation procedure of the operating conditions of electrochemical sensors (mainly dissolve oxygen and pH sensors for on-line monitoring of water). Such self-validation procedures increase the operating life and the reliability of a sensor, and extend the time-between calibrations or replacements of chemical consumables (electrolyte). The proposed technique is mostly suitable for stand-alone monitoring systems (such as data-loggers or remote stations) which operate continuously in the field of environmental monitoring of water ecosystems (on-line monitoring). This work uses a microcontroller measuring scheme in order to implement the above functionalities and proposes a measuring circuit (that is also described) which is needed to implement such "intelligent features".

I. Introduction

The rapid decrease in the cost of microcontrollers along with the increase of the on-chip capabilities have resulted in making microcontrollers the most essential part in modern instrumentation. Although most basic tasks associated with the front-end electronics of an instrumentation system are analog (sensor interfacing, signal amplification, filtering, etc), the single chip microcontroller is the core unit right afterwards, even in small and low cost systems. Quite complicated tasks may now be implemented by small microcontrollers at low cost and certainly in a small-volume instrument. With the recent advances in memory technology, larger algorithms and mathematical operations may be performed in reasonable time. Along with the improvement of these capabilities, the increased complexity of the microcontroller-based tasks results in measurement systems with "intelligent features". Sensors that combine such "intelligent features" can also be described as smart sensors. Smart sensor and smart sensor networks go beyond raw signal data, and provide certain level of information and knowledge, which can significantly improve the overall system performance [4]. One of the important abilities a smart sensor can have is self-validation [2].

Numerous tests with different purposes may be applied to a sensor during its life, each having to meet specific requirements. Diagnostic capabilities are mostly desirable to allow fast defect location in a complex monitoring system. The test of complete subsystems and systems consisting of numerous modules is a challenging task that becomes more important as system complexity grows. Testing is an essential way to ensure that the system operates in a fault-free condition. The tests discussed so far are applied off-line. On the contrary, there are on-line tests that are applied while the sensory system is performing its assigned task. Two types of on-line tests are distinguished, but may be effectively combined: The first one is the periodic tests in which the normal system operation is interrupted, which means that are performed regularly for short periods. The second one is the concurrent tests, which means that the system operation is checked actually in parallel to normal system operation, on the basis of additional information by additional hardware. A complete different approach is related to maintenance tests, which are performed to check proper system functionality either regularly or after upgrades. Such tests often require the interruption of normal system operation. A very intuitive test approach is to directly demonstrate that the specified function of the circuit (as a black box) is performed. The functional test is based on the circuit specification alone; no information on the internal structure is required [1].

II. The Sensors

This work is about the implementation of such methods to specific sensors which are widely used in environmental monitoring of water. The sensors that are of interest in this work are electrochemical

sensors that measure quantities like oxygen dissolved in water or pH. These sensors usually have a rather slow measurement rate and their response change as time passes since they consume electrical energy and chemical consumables (electrolyte) as well. For example the oxygen sensors measure the partial pressure of oxygen present at the membrane. The electrochemical reaction of the probe consumes all oxygen inside it. There is therefore a partial pressure difference across the membrane that only depends on the partial pressure outside the membrane - there is no oxygen on the inner side of the membrane. Oxygen thus diffuses through the membrane at a rate proportional to the oxygen partial pressure outside the membrane.

Each oxygen molecule that enters the probe transfers an electrical charge between the cathode and anode, creating an electrical current proportional to the oxygen partial pressure outside the probe. This current, either directly or transformed to a voltage, forms the output of the probe. To find out what this output represents the probe needs to be calibrated first, by placing the probe somewhere with a known oxygen partial pressure - for example, in the air.

The basic functionality of an oxygen sensor is similar to a current source. The lifetime depends on the amount of electrolyte and material present for the reaction, as well as the exposure to oxygen, but lies generally in the range of months up to few years. The major disadvantages of the standard electrochemical oxygen sensor are a cross-sensitivity to carbon dioxide and a tendency to form a carbonate layer on the internal lead electrode when high concentrations of carbon dioxide are encountered regularly. Added to the limited lifetime, this is a serious disadvantage. The great advantage is the simplicity of the sensor and measuring circuit, and a relative lack of sensitivity to pressure changes. The lifetime of the electrochemical sensor can be increased by leaving it open circuit when the instrument is switched off, but this has the disadvantage that the sensor takes some minutes to settle down after reconnection. The commonest solution is to short the terminals of the sensor when not in use. This detracts from the lifetime of the sensor, but means that the sensor can be used immediately after switching on.

The experimental measurements held are the monitoring of the transient waveform of the power consumption of the sensor during the start-up phase (current drawn by the sensor from the battery). Such sensors usually provide a 4-20mA output that is being read by placing a proper resistor value and by measuring the voltage drop on this resistor. The idea is to study the behavior of the output of the sensor with the help of power consumption measurements during the start-up phase in order to make conclusions about the status of the sensor and consequently about the correct operating condition of the sensor (i.e. need for re-calibration). This measuring scheme can be a part of a built-in self-test implementation placed along with the complete instrumentation system and thus include the monitoring of the sensor to this already existed monitoring of the rest of the system [6].

III. The Measuring Scheme

The above type of measurements can be realized by a specific configuration which has already been proposed by the same group for other (similar) type of measurements [5]. This configuration, shown in Fig.1 has been developed for monitoring and recording the current that a system draws by its power supply. This system was initially created for monitoring digital processing systems when executing different tasks in order to explore the relation between software tasks (execution of routines) and the power consumed by the system. Many efforts have been made in the direction of power optimization of digital systems for low-power applications. Some of these works focus on the theoretical analysis of a system and on the extraction of its power behavior based on it. This paper is interested in conducting real measurements on estimating the power consumption of a Device under Test (DUT) rather than estimating the power consumption by theory. Some approaches have been proposed that indicate possible ways of measuring the power consumption of a digital system in simulation. One of these approaches has been realized on the laboratory and some indicative measurements on real digital systems have already been performed.

The proposed measuring scheme consists of a current mirror with the Device under Test on the input branch and a combination of capacitors on the output branches. The current mirror creates duplicates of the current that is being drawn by the DUT. These capacitors, along with the rest of the circuit, are in charge of summing this duplicated current. The capacitors keep charging alternatively and when they are considered fully charged, a proper circuit discharges them. The alternative charging ensures that the input current is being monitored all the time, no matter if a discharging must take place. The rate of discharges is an indication of the energy consumption of the DUT. An important action on the development of this circuit is the extraction of the relationship between the average input current and the measured number of events, with the microcontroller as the recording system. This relationship can be obtained from the operation of the circuit since we are able to calculate the average

input current by simply measuring the resulting number of events. A repetitive set of measurements has been made in order to be able to calculate an equation with the help of curve fitting statistics. The resulting simplified equation is

$$N = 82400 * I_{in} + 136 \tag{1}$$

where I_{in} is the input current and N is the measured number of events. The thermal noise on the above measurements is below 1%. By reversing this equation, it can provide us the ability to estimate the average input current that corresponds to a measurement that took place.
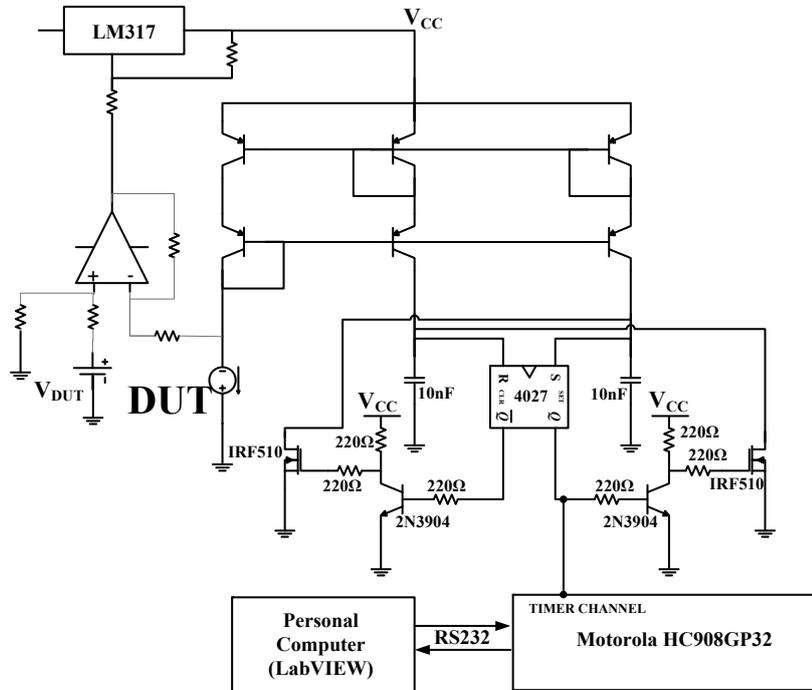

Fig. 1 – The energy consumption measuring configuration

If a specific time window is defined then the number of discharges that will take place within this window is indicative of the energy that was consumed in it. The measuring scheme is able to measure the energy consumption for the time window chosen. Specific operations on peripherals used in digital systems are usually controlled by some kind of on-off control signals that can easily be read on a microprocessor. These signals will indicate to the processor the limits of the time window that contains an operation, and so the energy consumption for this specific operation can be measured. Thus, if we are able to define the time limits of specific operations on the modules under evaluation then an accurate measurement of their energy consumption can be held.

So, a measurement is the recording of such a number for specific time windows. After this recording, an average current value can be calculated from the measured number with the already estimated equation 1 and thus the energy consumed for the specific time window becomes known, since we already know the time duration and the operating voltage. This procedure is controlled totally by a microcontroller (Motorola HC908GP32) with a lot of capabilities. The processing of the measurements can be held either on the microcontroller or even better on a personal computer, after the transfer of the measurement to it through serial communication. The microcontroller can be in total control of the measuring procedure without the need of a human user, and so the automation of the system can be really advanced. Also, this measuring system can be implemented as a peripheral module on a system that uses such a sensor and thus provide built-in self test abilities to this system. Obviously the DUT may be the electrochemical sensor itself or the complete system that utilizes measurements by using this sensor.

This system is not supposed to be used the whole time, because in this situation the consumption of the total system will be almost doubled. On the contrary, the DUT will be connected at specific test time windows and for a short duration. These time windows can be really small in duration compared to the magnitude of time in phenomena related to these measuring applications. Furthermore, the use of a microcontroller in charge of the measuring procedure can add more intelligent features to the system,

abilities that characterize smart sensors. The self-validation method for example can be implemented and thus increase the life and the reliability of the modules under evaluation. Also techniques that come from statistics, like smoothing and averaging, can be used in order to improve the accuracy of energy measurements without the need of a large number of measurements and thus minimizing the acquisition procedure.

IV. Measurements

The basic advantage of this approach is that a transient waveform of the current drawn from the source during a certain time interval may be recorded as a small set of numbers (the number of times that one of the capacitors is concidered fully charged in the above mentioned system). In this way the information about the correct (prototype) response during the start-up transient of the sensor can be stored in the microcontroller's memory and used later on for comparison as this transient drifts in value and time response. In general, interesting information about this output is the start-up current that appears when the sensor is warming-up. The current there is slowly changing in time until it reaches its final value. The duration of this procedure may vary from sensor to sensor and also may depend from the state of the sensor. These sensors depend on an electrolyte which changes in time, and if the sensor has been used properly or not, or if the sensor has been used for a long time and has aged, then this curve will be expected to became slower in time, and the final value is expected to be reached slower than in new sensors. The comparison with a known behavior may indicate a possible decay of the sensor or even a complete malfunction.

At this point, a brief explanation of the methodology that is being used from the measuring system will be presented. The measuring system coexists with the DUT and stands idle for the most of the time at a low power mode. The output branches of the current mirror of figure 1 are disabled and thus there is not any additional energy consumption by the measuring system. In a scheduled time on the measuring system an evaluation is programmed. The sensor will firstly be disconnected from its main system and then it will be connected to this measuring module. The disconnection will be only for a short time, so the evaluation time will be small and thus will not create an important disturbance to the operating system that contains the sensor. The evaluation procedure includes first a power off of the sensor (which is already operating normally) and then a power on. While the power on is happening the resulting current of the sensor is being recorded. This is done by using the measuring scheme for sequential time windows of about 150ms each one in duration and almost no delay among them. After these measurements, the resulting numbers are about to be compared with already known values, and the valid operating condition of the sensor is to be evaluated. If the sensor appears to be malfunctioning, the measuring system must announce it with a proper way to a human user, with even a simple response as lighting a led. If the sensor appears to operate properly, then it is switched back to its main system and the measuring system turns idle until the next evaluation.

Three sensors have been evaluated in the water with different operational status for each one of them (different quality of the electrolyte). The resulting waveforms are illustrated in figures 2, 3 and 4. In every situation, the sensor is firstly being powered off and then powered on by the measuring system.
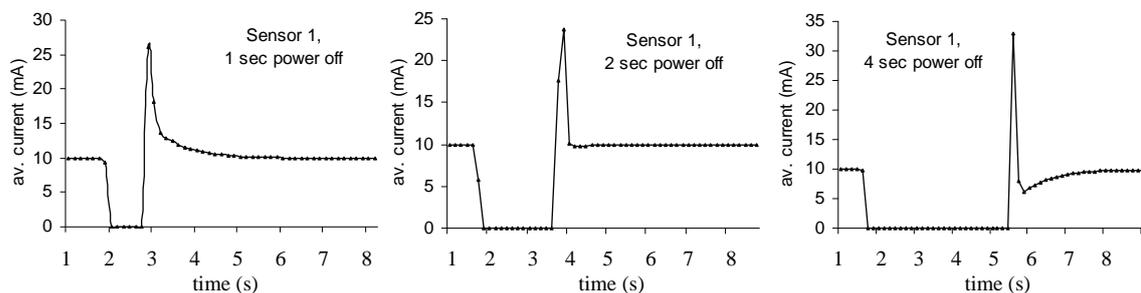

Fig. 2 – Measurements taken on the first sensor

The disconnection duration varies to the values of 1, 2 and 4 seconds. That is because after initially exploring the energy behaviour of these sensors, they indicated a small difference in their response as this disconnection duration changed. Every point of the waveforms on these figures indicates an average current value for a time windows of about 150ms. The zero values are describing the sensor while it is powered off, and after that the following points indicate the behaviour when the power on is happening. The first sensor (figure 2) is fully operational with fresh chemicals (electrolyte) and recent calibration and is considered to be a good sensor, while the second one (figure 3) is without electrolyte and the third one (figure 4) is with electrolyte that is not of good quality. The electrolyte can become of

bad quality after being used for a lot of time. The last two sensors are considered as examples of sensors that are not in a good condition. The third one is able to measure oxygen but is considered in a condition that is close to becoming a malfunctioning sensor.
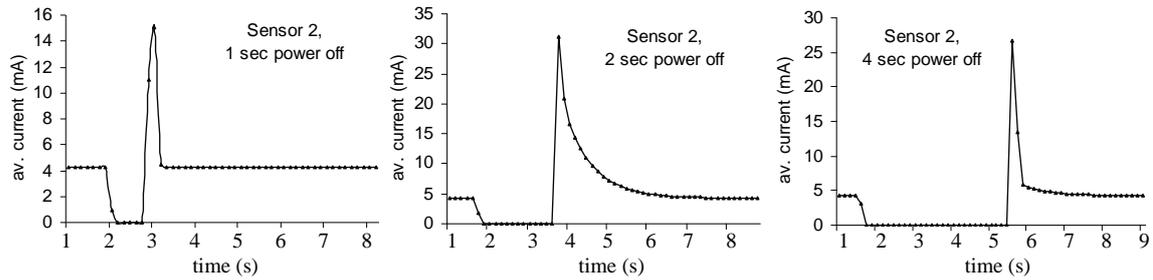

Fig. 3 – Measurements taken on the second sensor

First of all, the sensor with no electrolyte (figure 3) is described by current values a lot different compared to the other sensors. So, even only these values can be an indication of a malfunctioning sensor. Furthermore, the curve shapes for the same power off duration have differences between them. In the situation of a 4 second power off, there is no diving to lower values than the final steady value for the second sensor, while such a dive appears to the rest two sensors. Differences also appear on the rest power off duration curves. So, these waveforms can indicate a sensor that has gone completely malfunctioning.
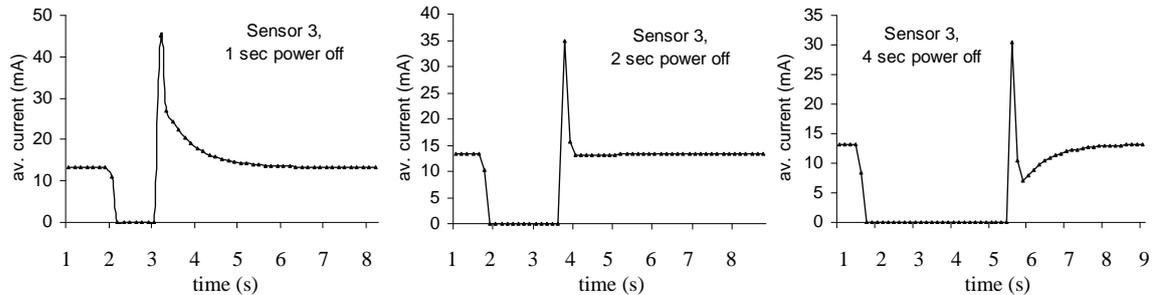

Fig. 4 – Measurements taken on the third sensor

In figure 4, we observe waveforms that have some differences compared to the waveforms of figure 2, where a good sensor is presented. In this third sensor, in the waveforms concerning power offs of 1 and 4 seconds, we observe a voltage spanning in each waveform that is larger than the one that appears on the waveforms of figure 2. This means that this sensor tends to reach the final steady value at a slower rate compared to the first sensor. So the measurement of this spanning can become a way of defining the quality of the electrolyte in each sensor.

The curves of figures 2 and 4 indicate a behaviour that can be controlled and used as a reference indication and that the proposed measuring system is able to implement evaluation tests to the mentioned sensors. Also, all these measurements indicate a behaviour that provides stabilized current values within only a few seconds, so in a situation that the sensors take a lot of time for reaching the final steady value, this will be an indication of a malfunctioning sensor. Finally, these sensors were evaluated also on air and appeared to have differences almost unnoticeable and only due to small differences on the temperature values between the air and the water.

V. Conclusions

In this paper, an attempt is being made in order to evaluate sensors based on power measurements. These sensors are based on electrochemical phenomena and in general show a behavior that changes in time because of the 'aging' of the sensors. An analysis of the problem of the proper monitoring of such sensors has been presented, and also the measuring scheme available for these measurements has been described. Abilities of such a system that rely on a microcontroller have also been mentioned. Measurements on real oxygen sensors have been shown and analysed. These measurements proved that the estimation of the good operating condition of these sensors can be realised by such an approach.

References

[1] Voulgaris A., Laopoulos Th., "An intelligent microcontroller-based configuration for sensor validation and error compensation", IEEE Instrumentation and Measurement Technology Conference, May 2003, USA

[2] Satnam Alag, Alice M. Agogino, Mahesh Morjaria, "A methodology for intelligent sensor measurement, validation, fusion, and fault detection for equipment monitoring and diagnostics", *Artificial Intelligence for Engineering Design, Analysis and Manufacturing 2001*, issue 4, Vol 15, pp 307–320, Sept 2001

[3] Gong S., White M.H, "An automatic measurement system for electromechanical characterization of silicon pressure sensors", *IEEE transactions on instrumentation and measurement 1996*, Vol.45, issue 1, pp 184 – 189, Sept 1996

[4] Yong Zhang, Yikang Gu, Vlatkovic, V., and Xiaojuan Wang, "Progress of smart sensor and smart sensor networks", 5th World Congress on Intelligent Control and Automation - WCICA 2004, China

[5] V. Konstantakos, K. Kosmatopoulos, June 2004S. Nikolaidis, Th. Laopoulos, "Measurement of power consumption in Digital systems", *IEEE Transactions on Instrumentation and measurement*, Vol.55, No.5, October 2006

[6] Konstantakos V., Laopoulos Th.," Monitoring and analysis of power consumption in data logging systems for built-in testing", DCIS´06, XXI Conference on Design of Circuits and Integrated Systems, 2006, Spain

[7] Chiyoung Seo, Sam Malek, and Nenad Medvidovic, "A Generic Approach for Estimating the Energy Consumption of Component-Based Distributed Systems", Technical report USC-CSE-2005-506, University of Southern California, Center for Software Engineering, April 2005