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A robust cell voltage monitoring system for analysis and diagnosis of fuel cell or battery systems

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ABSTRACT

Cell voltage monitoring (CVM) systems are essential for the operation of fuel cell stacks and some battery systems, in the field as well as in the laboratory, because they allow the diagnosis and correction of problems that would otherwise go unnoticed and cause impaired performance or even permanent damage. A robust, safe, and low-cost design for a CVM unit is presented, using electromechanical relays as multiplexing switches. Some examples from the application of the unit on the University of Delaware's fuel cell battery hybrid buses are presented, including its use in automatically correcting anode flooding and diagnosing air channel blockage.

1. Introduction

Measurements of voltage and current from a single operational fuel cell help in understanding the influence of various parameters on cell performance [1]. A fuel cell stack is a collection of individual cells electrically connected in series. In an ideal fuel cell stack, every cell would be subjected to identical operating conditions and the overall stack performance would be obtained as the sum of the identical outputs of individual cells. However, it has been observed that due to manufacturing variability of components, stack architecture, and degradation with use, individual cells in a real stack will typically show some variation in performance depending on the specific operating conditions. Hence there is a need for a cell voltage monitoring system (CVM) which can detect significant deviations from the desired behavior and initiate corrective measures [2]. Similar considerations exist in battery systems [3]. Simple CVM systems have been designed to explore the coupling between adjacent cells and to quantify the influence of variations in operating conditions [4,5]. For large stacks, there are additional factors that must be carefully considered in the design and implementation of a robust cell voltage monitoring system.

The function of a CVM is to acquire voltages from the cells of a fuel cell stack or battery string. Its application can be as simple as comparing each cell's voltage to a specified minimum or maximum value and trigger an alarm if any cell voltage is out of range, or it can involve measuring cell voltages with respect to time, current, or other independent variables such as temperature, air flow rate, or humidity. CVM is a useful tool, either in an experimental or prototype fuel cell or battery system where it can diagnose design problems, or in regular production use [6]. For example, a fuel cell stack can be operated at higher power levels if cell undervoltages can be actively detected, rather than passively avoided by operating the system conservatively. Similarly, the safety and longevity of batteries can be enhanced by actively monitoring individual cell voltages during plug-in charging periods or during vehicle operation. CVM is most often used to monitor individual cells when fitted to strings of cells that are particularly intolerant of voltage excursions, such as fuel cells or lithium ion cells, but other cell chemistries such as flooded lead–acid, nickel–cadmium, or nickel metal hydride may be able to operate safely without per-cell monitoring. In those cases, cost can be reduced by monitoring small groups of cells; for example, the voltage of each battery block (containing a few cells connected in series) might be monitored rather than looking at the voltage of each individual cell.

When cell voltage is measured with respect to current, it is called a polarization curve, since it reflects the various sources of polarization (reduction of voltage from the thermodynamically reversible level) in a fuel cell or battery. Producing polarization curves for each individual cell provides important clues about the system's performance and efficiency. CVM data allow the performance of all cells to be continuously compared in order to diagnose stack faults and performance loss in real-time. The CVM architecture presented here allows this technology to be implemented at low cost and with high reliability. Some examples demonstrating the utility

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of our CVM system in our fuel cell battery hybrid buses are also presented.

2. Challenges in CVM implementation

2.1. Cost vs. speed

Implementing cell voltage monitoring in a fuel cell stack or battery system, which may contain over a hundred cells, presents several challenges. The most obvious is the cost of such a system; it must include at least one element that is repeated for each cell. If the system includes a continuously operating input channel for each cell, it can become quite expensive: the isolated Analog-to-Digital Converter (ADC) and associated power supply developed at UD would cost over $3000 in parts alone to build 100 units. Isolated comparators, especially fixed voltage types, can be much less expensive and are practical to implement with dedicated units; however, they are of limited diagnostic use.

The use of a dedicated input channel for each cell can be avoided by multiplexing cell inputs and using a smaller number of ADCs, which are then used to scan the cells [7,8]. Such a multiplexed CVM is shown schematically in Fig. 1. Switching elements (e.g. relays or transistors) are approximately an order of magnitude less expensive than ADCs. Multiplexing offers the additional benefit of reducing circuit board footprint as compared to individual ADCs, since a relay can be made smaller than an isolated ADC circuit.

The disadvantage of multiplexing is that it reduces the rate of data acquisition while monitoring the entire stack, principally due to settling times needed when switching between cells; a high-speed ADC can acquire samples at 100 kHz or higher, whereas a multiplexed system may require 10 ms or more to switch from one cell to another. If a stack of 100 cells is being scanned by one ADC, this means the multiplexed system will provide updates for any given cell at 1 Hz. Depending on the use of the data and the nature of the system, this may be acceptable or quite problematic. The rate of acquisition can be increased by adding ADCs: using 10 ADCs instead of one in the previous example would give an update rate of 10 Hz, with increased cost due to the additional ADCs.

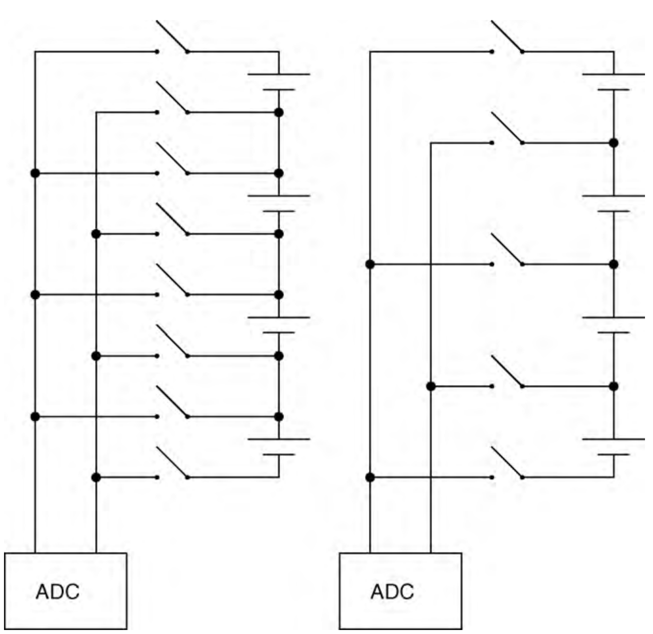

Fig. 1. A multiplexed CVM, shown here set up for four cells. Note that if the ADC can work with reverse polarity, the number of relays can be reduced, as shown on the right.

2.2. High voltage

Another challenge in assembling a practical CVM system is maintaining electrical safety and measurement accuracy in the presence of high voltages from the stack; a stack of 100 Proton Exchange Membrane Fuel Cells (PEMFCs) can attain an open-circuit voltage of 100 V or more, which in the event of a fault can cause serious equipment damage or injury to personnel. All isolation and switching circuits are subject to failure; in a multiplexing switch, if a switching device fails as a short circuit, then when another device is turned on to connect another cell to the same terminal of the ADC, one or more cells will be shorted out through the CVMs circuitry (Fig. 2). This can result in dangerous fault currents, so some form of fail-safe protection is needed between the stack and the CVM. This may take the form of fuses, series resistors to limit fault current to a safe level, or some other device. Each method has its drawbacks: fuses able to interrupt high DC voltages are rather large and expensive, and series resistors introduce error to the data in proportion to the ADC's input current.

A further concern is that most ADCs cannot operate with input voltages greater than about 20 V. Since our objective is to measure cell voltages in a stack with much higher voltages, we must either reduce the input voltages, using some form of signal conditioning, or isolate the ADC, so that its ground reference can change to a potential conveniently near that of the cell to be measured.

Two approaches are commonly taken for signal conditioning; however, both have serious drawbacks. The first is the resistor divider (Fig. 3), where two resistors are connected in series between each cell and a ground reference, and the ADC measures a voltage that is some fraction of the original input voltage, determined by the ratio of the two resistances. The second is the resistor-diode (Fig. 4), as implemented by Webb et al. [9], where each cell has a single resistor and protection diode connected to the ground reference, and voltage measurements are made by connecting cells' resistors to ground through a low-impedance current measuring device and determining voltage using Ohm's law. When a cell's voltage is not being measured, the protection diode conducts and maintains the voltage at the switching device at a level equal to the diode's forward voltage drop above ground (normally around 0.6 V), allowing the use of semiconductor switching devices that cannot tolerate the full voltage of the stack.

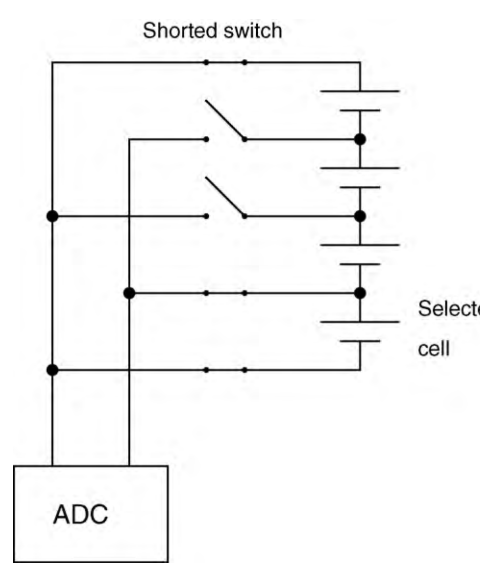

Fig. 2. A CVM with a shorted switching device. When the switches for the selected cell turn on, fault current will flow through the shorted switch and one of the activated switches.

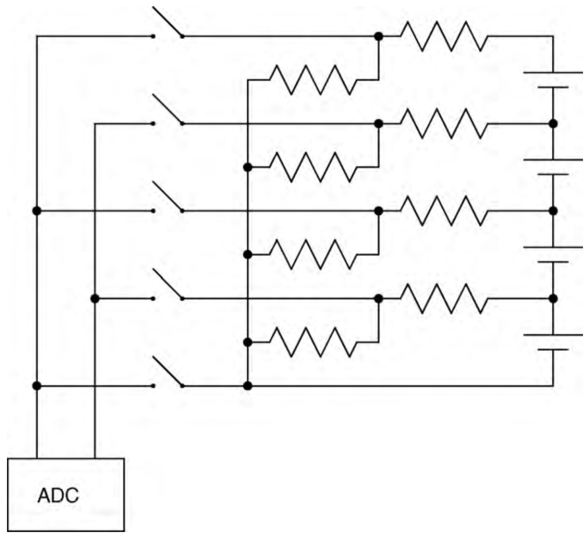

Fig. 3. A resistor-divider architecture.

Both of these approaches have problems with uncertainty in resistor values: if 0.1% tolerance resistors are used to determine the voltages relative to ground of the two plates adjoining a cell, these voltages will have an uncertainty of 0.1% of the voltage relative to ground in a resistor-diode system with perfectly calibrated current measurement, or 0.2% if the resistor-divider method is used. The uncertainty for the *cell's* voltage is the sum of the uncertainties of the two plate voltages subtracted to determine it, which can be a serious problem in systems with large numbers of cells; for example, scanning a 110-cell stack using the previously mentioned resistor-diode system with 0.1% tolerance resistors, a typical operating voltage of 0.6 V per cell would give an uncertainty of 0.1314 V on the highest voltage cell, 21.9% of the value being measured! This error can be calibrated out, but only if temperature is kept constant; as Webb et al. [9] point out, the problem only gets worse when temperature is allowed to vary, as seen in most field applications of fuel cells, since resistors typically have substantial variation in their value with temperature. This is a difficult error to correct, since it requires controlling or monitoring the temperature of all the resistors involved. These problems make the additional cost of an isolated ADC more palatable.

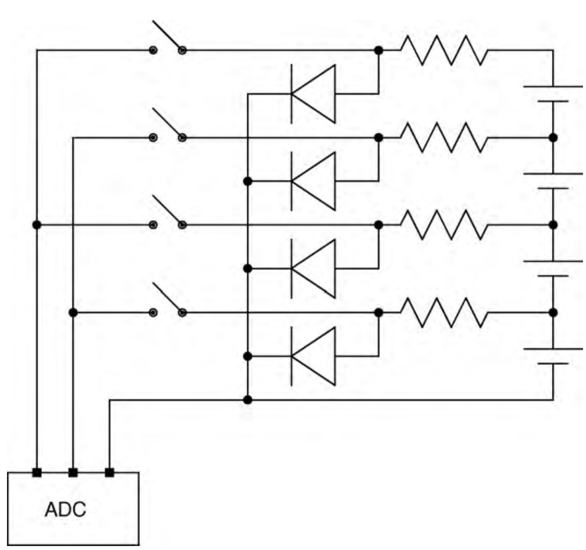

Fig. 4. A resistor-diode architecture.

2.3. Electrical noise

Finally, CVMs face the challenge of electrical noise, mostly switching noise from power converters. A fuel cell will often have a power converter at its output so it can provide varying amounts of power to a system with fixed or independently varying voltage, and the fuel cell system may contain many other switching devices such as inverters to feed air compressors and pumps. All these sources of noise introduce error into the output data, which may be constant or form a beat frequency (if the ADCs clock frequency or the frequency of cell acquisition is near to an integer ratio with the converter switching frequency), or apparently random. Removing this error requires some form of filter, which can be implemented with analog components, a digital algorithm, or some combination of the two. Its form will be highly dependent on the nature of the noise and how quickly data must be acquired; generally, the more noise is removed, the slower data acquisition becomes.

2.4. Addressing the challenges

In this paper, we present a CVM design that overcomes the challenges stated above and demonstrate its use in two operational fuel cell hybrid buses at the University of Delaware. The buses are both 22-foot transit style vehicles made by EBus, Inc. of Downey, California, USA, equipped with 60 kWh of Ni–Cd batteries, electric drive systems, and Ballard Power Systems Mk. 9 SSL 110-cell fuel cell stacks, with the balance of fuel cell plant provided by EBus. The first vehicle, delivered in February 2007, has a single stack, and the second, delivered in May 2009, has two stacks connected in series [10]. Upon delivery to UD, the stacks on both vehicles were instrumented with CVM systems to better characterize their performance and diagnose problems.

3. CVM design and fabrication

The UD fuel cell buses employ a series, battery-heavy hybrid platform which implies that the load on the stack does not experience abrupt changes. Our measurements show that the fuel cell stack's load changes are typically less than 2 A s^{-1} on a stack rated for 300 A, with typical operation periods lasting a few hours. Therefore, the CVM system developed for this project uses a single isolated ADC and relays to multiplex signals with a overall system scan time of 5.5 s (50 ms settling time is allowed for each of the 110 cells to minimize error). Further details about the CVM architecture are presented below.

3.1. Fault protection resistors and isolation

Since space for the system was limited and would not accommodate appropriately rated fuses, 10 kΩ series resistors were used to provide fault protection. For additional safety (and to allow accurate voltage measurements), an isolation barrier was provided between the high voltage system and the low voltage power and communications circuits.

Relays were chosen instead of optically coupled MOSFET switches because of the MOSFETs' high leakage current at elevated temperatures: 1 μA of leakage current per device, which is within most devices' ratings at the stack's operating temperature of 70 °C, would introduce an error of 10 mV per device when dropped across the 10 kΩ protection resistor. Unfortunately, leakage current is not at all consistent from one device to another, so this error can assume random values between 0 and 10 mV. Furthermore, a practical system has many switching devices connected to each ADC input terminal, each delivering a random leakage current, so that the total error is *the sum of the errors introduced by*

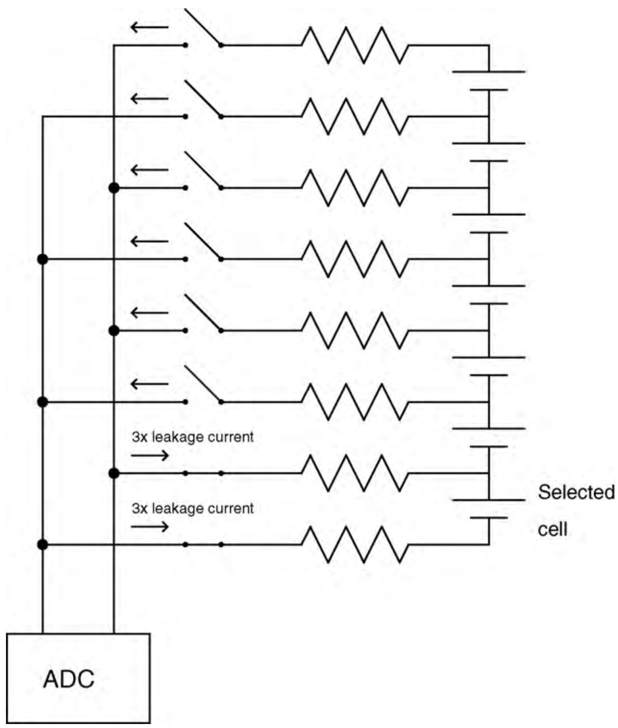

Fig. 5. Illustration of the error produced by the summed leakage currents of inactive switches, shown for the case of a 7-cell stack. If each switch had a leakage current of 0–1 μA, each resistor on the selected cell would see an imposed current of 0–3 μA. If the resistors were 10 kΩ, this would give an error of ±30 mV in the cell voltage (one input to the CVM has a negative sense and one a positive sense, so the error can assume either sign).

each switching device. The error produced by the summed leakage currents of inactive switches is depicted in Fig. 5. In a system with more than a few cells, the problem would be quite serious: a 110-cell system has 109 inactive devices at any moment, giving an error range of ±545 mV, possibly greater than the value being measured. Systems employing multiple isolated ADCs, as described by James [8], have fewer devices connected in parallel, and the smaller voltage range seen between the signals connected to each ADC allows the use of lower valued fault protection resistors. They may thus be able to employ semiconductor switches without problems. However, as mentioned before, this entails extra cost for the additional ADCs, and such a system would also need protection against failures of isolation devices. Otherwise, an isolation failure could connect high voltage fuel cell plates to low voltage control circuitry through a resistor that is unable to withstand the applied voltage.

By comparison, relays are readily available with an insulation resistance of 10^{12} Ω. This means that, in a system with a maximum stack voltage of 110 V, the worst-case leakage current is 110 pA instead of 1 μA, reducing the error by a factor of 9091 to 0–1.1 μV per device. In the 110-cell application at UD, the maximum total error resulting from this leakage would be 60.5 μV, since the leakage current is proportional to voltage across the relay, and the average voltage across a relay is equal to half the maximum voltage of 110 V. Relay life is very good with currently available devices; the relays used in the UD CVM system are rated for 10^9 make-break cycles each.

The UD CVM system is depicted in Fig. 6. To reduce cost, the relays connected the cells' bipolar plates to alternating terminals of the ADC: all odd-numbered plates were connected via relays to one terminal, and all even-numbered plates were connected to the other. This configuration required $N+1$ relays, where N is the number of cells, rather than $2N$ relays, which would be required to allow any cell to be connected to either terminal of the ADC. This had the effect of connecting every other cell to the ADC in reverse. Additionally, the relays were activated using cross-point switching, which minimizes the number of digital outputs required from the microcontroller and simplifies board layout. Instead of having one output for each of the 111 relays, the relays are assembled into two 7×8 arrays (one for all the even-numbered relays, and one for all the odd-numbered relays, so that only one relay from each array will be activated at a time) and diodes are installed in series with the relay coils. This allows a relay to be selected by driving its "row" connection (carried in buses labeled 12a and12c in Fig. 6) low and its "column" connection (buses 12b and 12d) high, and reduces the number of digital outputs needed from 111 to 30.

3.2. Low pass filtering

Electrical noise presented a serious challenge on the bus, since it has a boost converter on the fuel cell output and 12 other large switching converters (mostly inverters to drive motors). Since the frequencies of these devices are not all fixed, low pass filters were employed instead of bandstop arrangements. The 12 V DC power supply to the CVM was filtered with a second-order LC circuit. The signal to be digitized was filtered with a first-order RC circuit that combined the 10 kΩ protection resistors with a 0.1 μF capacitor for a cutoff frequency of 80 Hz (two 10 kΩ resistors were connected in series with the capacitor), and then by a fifth-order moving average digital filter implemented within the ADC chip. Because of the long settling time of the RC filter, an "even-then-odd" (all even cells and then all odd cells) scanning pattern was used, so that the filter would normally have to swing by less than 100 mV from cell to cell, rather than 1.2 V or more to go from a cell connected forwards to one connected backwards.

It may be possible to reduce the scan time significantly (from 50 ms per cell to a value on the order of 3 ms per cell) by providing a dedicated filter capacitor for each cell, rather than using a single filter capacitor that must charge or discharge through the protection resistors to reach the voltage of the cell being measured. Reed relays can easily close and open in less than a millisecond, and the ADCs digital filter will converge to steady state in approximately one millisecond with the clock frequency used in the UD CVM. This approach is currently under investigation, and results will be reported in a future paper.

3.3. Isolated ADC

In an earlier version of the CVM, an Analog Devices AD202KN analog isolator had been used to transmit the cell voltage information across the isolation barrier as an analog voltage, which was then converted to digital form by the microcontroller's built-in ADC. This was replaced with a separate ADC, digital isolator, and isolated push–pull power converter; the ADC was connected directly to the relays, powered by the push–pull converter, and control and data signals were sent through the digital isolator. This arrangement saves board space and cost, allows the use of a more accurate ADC than the built-in unit, and also improves noise immunity due to the lower isolation capacitance of the isolation transformer and digital isolator as compared to the analog isolator. If isolation capacitance is large, the high-frequency noise components of the voltage measured by the CVM produce significant leakage currents across the isolation barrier, which are picked up by signal processing circuits and impact the measurements being taken (especially if the leakage currents are not equal between the two inputs to the ADC or isolator).

The isolated ADC used provides quite accurate measurements despite the error introduced by various sources such as leakage cur-

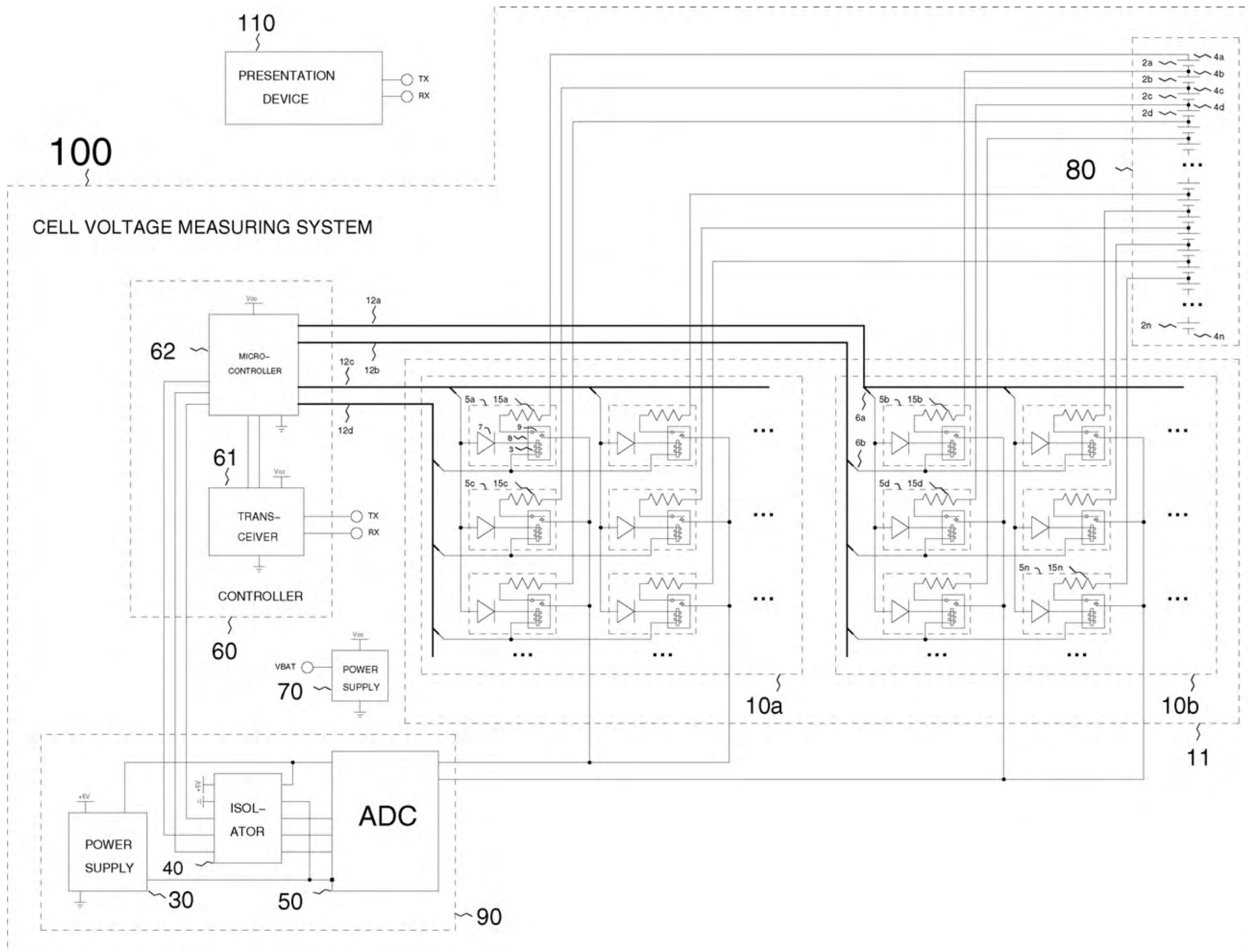

Fig. 6. The UD CVM system, shown with a subset of the relays and cells used for clarity. The arrays of relays are both 7 × 8, giving 112 relays (one is not used, since there are only 110 cells in the stack and therefore 111 bipolar plates). This circuit fits on a 10.9″ × 3.65″ board.

rent through the switching relays and protection diodes, reference voltage drift, input amplifier offset voltage drift, input leakage current drift, ADC offset and gain drift, and high-frequency noise from the switching converters in the high voltage system being monitored. The total contribution from these sources is not expected to exceed 4.52 mV for a cell voltage of 1 V over an operating temperature range of 0–50 °C. It is in fact likely to be considerably less, since 2.6 mV of it is due to input amplifier offset voltage, which can be zeroed at the same time as ADC offset and gain errors are calibrated out.

To evaluate the real-world performance of the CVM, it was tested on the fuel cell system used on the University's Phase 1 fuel cell bus and compared with a Fluke 87-V hand-held multimeter. Three data points were collected at voltages near 0.01 V (fuel cell shut down), and 10 data points were collected with the system at moderate load with cell voltages near 0.72 V, with current drawn from the fuel cell by the switching boost converter (expected to be the primary source of electrical noise in the fuel cell system). All measurements matched to within the 1 mV accuracy of the Fluke 87-V. The CVM tested was not equipped with protection diodes, but those would contribute at most 0.8 mV more error. This compares favorably with the 10 mV accuracy of the system described in [6] and the 30 mV accuracy of the system described in [9] (which would worsen considerably in field conditions without temperature monitoring and/or control on all the resistors used). In addition, because of the lower number of ADCs, the system described here is likely to have a lower construction cost than the systems described in [6,8], and only a slightly higher cost than the system in [9].

4. CVM for data analysis and diagnosis

4.1. Low/high voltage cell detection and protection

One of the major uses for cell voltage monitoring, as mentioned earlier, is detecting excessively low or high cell voltages. This is an important task for a fuel cell system, since it is quite possible for cells within a stack to underperform while the stack voltage remains high enough to cause no concern. Individual cells can be depressed in voltage due to a number of factors, most often either undersupply of gases (due to clogging of channels by water or, more rarely, debris) or damage to the cell (such as delamination of components due to freezing).

An important point to keep in mind is that the resistance of bipolar plates can have a considerable effect on the CVM's ability to detect problems; particularly in stacks with long, narrow cells, a problem localized on one side may be almost invisible from the other. Both of the fuel cell buses have the stacks connected in "co-flow" configuration; that is, hydrogen and air flow in the same direction through the stack. Because many problems are the result of undersupply of gas to the fuel cell's active area, they tend to be more likely and severe in the areas of the stack closest to the gas outlets, where reactant flow rates are lowest, water content is highest, and oxygen depletion in air-breathing stacks is most severe. Consequently, the UD CVM system was connected to the outlet side of the stacks in both vehicles. In the previously mentioned example of blocked air channels on the dual stack bus, several cells were found to be at critically low voltages (less than 0.2 V) when measured at the outlet side by the CVM, where oxygen had been depleted from the inadequate air supply, but above 0.5 V when measured from the inlet side with a multimeter.

Cells can also suffer from what is sometimes called “hot spots”, a condition where a cell (or some portion of its active area) warms up, dries out, and operates at low efficiency because the membrane is no longer adequately hydrated. The condition starts when the cell’s operation is impaired by some other issue (heating the cell up because more energy is absorbed by the losses that are reducing voltage), and then self-perpetuates. However, the situation can be rectified with appropriate intervention.

Such intervention usually takes the form of reducing stack current and possibly increasing humidification, allowing the affected cell to cool down and rehydrate its membrane. A system without some means of actively detecting low or reversed cells would have to operate conservatively to avoid the condition, or carry out this current reduction on a regular basis to recover any cells that *might be* running hot, which would mean periodically producing low output power. Cell voltage monitoring to detect underperforming cells is therefore useful, and if this is the only goal of the system, the ADC can be replaced with a less expensive comparator circuit.

Ensuring that the cells stay within a safe range is also of vital importance in battery systems, particularly those with lithium chemistry. Lithium cells that are overcharged will generally suffer damage, and in some chemistries can experience thermal runaway; they can also be damaged by overdischarge. The CVM system described here can be used to detect and prevent such undesirable situations.

4.2. Diagnosing underperformance

Simply determining that a cell is underperforming is only part of what cell voltage monitoring can do; often, it can help in determining the root cause of the low cell voltage and choosing the best corrective action. For example, if a PEMFC’s anode is flooded and not receiving sufficient hydrogen, reducing stack current will protect it from damage, but purging the water with a burst of hydrogen will restore full power operation, which is obviously preferable in any real-world system. Some diagnostic examples are provided below.

4.2.1. Patterns in cell voltage vs. cell number

Certain problems cause characteristic patterns in the plot of cell voltage vs. cell number; for example, on the stack used on the University’s fuel cell bus, a cell that is starved for hydrogen due to anode flooding will exhibit low voltage compared to the stack median [11], and the two neighboring cells (or one, if the affected cell is at the end of the stack) will exhibit abnormally high voltage. This occurs because problems are often localized in one part of the stack, and in stacks with bipolar plates having significant resistivity, if one cell has an area that is malfunctioning, that area can “shadow” the areas cognate to it on adjacent cells, as described by Santis et al. [2]. If the fault is on the same edge of the stack as the CVM, this produces higher voltage readings on those cells because the shadowed areas are operating at lower current densities than the rest of the cell, and thus at higher voltages. Fig. 7 illustrates this phenomenon. This method does not always deliver unambiguous results; for example, the same “volcano” pattern can occur with internally short-circuited cells, when the fault is on the side of the stack opposite the CVM). Therefore, other methods must be used to determine the exact cause of the problem; examining the changes in voltage of a cell showing the “volcano” pattern as stack current changes can help to distinguish a short circuit from a blocked anode.

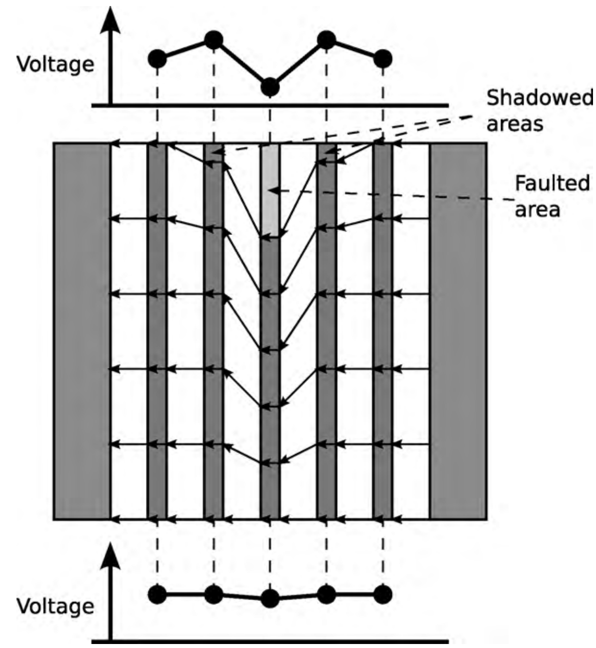

Fig. 7. The “volcano” pattern caused by a faulted area in a cell. The bipolar plates are shown in white, the membrane electrode assemblies are shown (not to scale) in dark gray, and the current collectors are shown in medium gray at the ends of the stack. Streamlines of current are shown with arrows to illustrate the lowering of current density in the shadowed areas. The “volcano” pattern is more apparent if the fault occurs near the same edge of the stack as the CVM-stack connection (see top of figure).

4.2.2. Patterns in cell voltages as reactant flows change

In many fuel cell systems, the fluid flow can experience rapid changes over time independent of system load; for example, most systems include some means of clearing the hydrogen circuit with a burst of gas, and some employ similar purges with the cathode circuit. Observing how the cell voltage changes in response to these events can be very informative; a low cell caused by anode blockage will normally reduce in magnitude or disappear during or after an anode purge, but an instance caused by an internal short will not change significantly. Similarly, if a cell’s cathode is flooded, operating with low air flow to the stack overall may cause a severely low cell voltage, while operating with higher air flow causes a near-normal voltage. The CVM data in Fig. 8 show the beneficial effect on cell voltages after a hydrogen purge cleared liquid water from the stack.

4.2.3. Patterns in cell voltages as stack current changes

Some problems show their characteristic pattern only with respect to current; for example, consider a fuel cell with a small internal short circuit and a cell with partial delamination of the catalyst layer from the electrolyte membrane. The cell with the internal short circuit will show much lower voltages than the others in the stack at low currents, but if the stack current is high, it will be significantly larger than the short circuit current and dwarf its effects on cell voltage, so that the cell appears almost normal. Conversely, the cell with the delaminated catalyst will appear almost normal at low current, because the intact portion of the membrane is able to supply the stack current without severe losses, but high current will overload the intact membrane area and give severe mass transport losses that may even cause negative cell voltage.

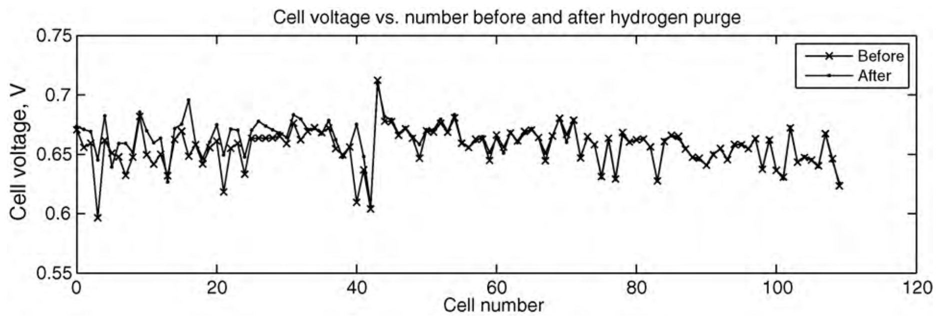

Fig. 8. Cell voltages on the Phase 1 single-stack fuel cell bus, shortly after system startup, before and after a hydrogen purge that cleared liquid water from the stack. Note the persistently low voltage on cell #42, caused by a mild internal short circuit, and the surrounding volcano pattern. In addition, the effects of greater purge flow through the low-numbered cells, which are closer to the gas ports, can be seen in the form of improved cell voltages.

It is also important to examine voltage at varying current in a battery system: a damaged or degraded cell may be indistinguishable from the rest of the pack at open circuit, but reach voltage limits far sooner than the rest when current is applied. Alternatively, a cell may be in good condition but have a state-of-charge different from the rest of the pack, in which case it will be noticeably different at open circuit but will track with the other cells when current flows. This condition can be observed and used to trigger a cell-balancing circuit.

In a battery system where series groups of cells are monitored rather than individual cells, examining changes in group voltage vs. current becomes particularly important. At open circuit, a cell with excessively low voltage (due to low state-of-charge or a damaged cell) could be canceled out by another cell in the same group with excessively high voltage due to high state-of-charge, resulting in a group voltage that appears normal. However, in most battery chemistries, discharging internal resistance increases rapidly when state-of-charge approaches zero, so the voltage of the already low cell would eventually drop under discharge much more than its neighbors', and the group's total voltage would no longer appear normal.

4.2.4. Other analysis techniques

Statistical analyses can be used to diagnose faults when a simple examination of the data is not enough to distinguish between a fault and normal operation, or when examining every cell individually is impractical. They may rely on comparing cell voltage data to some reference point; for example, on the Phase 1 single-stack fuel cell bus at UD, the fuel cell control system computes the RMS of the second derivative of cell voltage with respect to cell number, as shown below:

$$\sqrt{\frac{1}{N}\sum\nolimits_{i=2}^{N-1}(V_{i-1}-2V_i+V_{i+1})^2}$$

In the Ballard Mk. 9 SSL stack, cell voltage tends to decline with increasing cell number, since high-numbered cells are far away from the ports that supply reactant gases, and thus tend to receive less reactant and have lower voltage. The above RMS value largely ignores this trend, but still detects faulted cells (which are much lower than their immediate neighbors and therefore have a large second derivative of voltage with respect to cell number). If it is greater than an empirically determined reference point, hydrogen gas purges are conducted more frequently to attempt to clear anode flooding, which was found to be a major cause of low cell voltages, especially before the system reached normal operating temperature.

Other, more sophisticated analysis methods are possible: Xue et al. [5] describe a method for comparing the performance of a real stack to a validated model to detect fault conditions, while Riascos et al. [12] describe a system based on a Bayesian network programmed using data from experiments with deliberately induced fault conditions.

5. Summary

Cell voltage monitoring is an important diagnostic tool for fuel cell stacks and battery systems. It is particularly so in experimental or prototype fuel cell or battery systems, where it can diagnose design problems, but also in regular production use. This paper describes the design of a robust and low-cost CVM system employing a single isolated ADC and relays to multiplex signals with low pass filtering to reduce electrical noise. The application of the CVM to the University of Delaware's fuel cell buses has been demonstrated with several examples to show its utility as a diagnostic and analytical tool. It is shown that a fuel cell can be operated at higher power levels if cell undervoltage can be actively detected, rather than passively avoided by operating the system conservatively. Similarly, the CVM can play a useful role for battery systems where the behavior of certain battery chemistries makes active monitoring essential for their safety and longevity. Two CVM systems based on the architecture presented here are in continuous use in our fuel cell buses and are providing valuable data with high reliability.

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