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Measuring individual cell voltages in fuel cell stacks

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Abstract

The requirements for stack monitoring devices are becoming more strict as the fuel cell and battery technologies reach an advanced stage of development and move towards commercialisation. Different applications put restraints on such devices when it comes to cost, weight and size. No commercial products can meet the requirements with respect to both cost and performance. Individual cell voltage measurements are crucial to protect the fuel cell stack and ensure maximum stack lifetime. Different concepts for measuring individual cell voltages in large fuel cell stacks or battery stacks and their potential accuracy are discussed. A novel low cost, lightweight and compact multiplexer circuit was implemented based on a resistor–diode circuit. Based on this circuit a prototype 80-channel multiplexer device was built and tested on a fuel cell stack with satisfactory speed and accuracy.

Keywords: Fuel cell; Stacks; Voltage measurement; Multiplexer

1. Introduction

The performance of the polymer electrolyte fuel cell (PEFC) has significantly improved during the last few decades. Mainly due to enhanced electrocatalytic properties, power densities in the W/cm^2 range are now attainable. Development of the thin film technique [1] for preparation of catalyst layers was one of the main achievements that made the PEFC technology a viable energy conversion alternative. This 10-fold reduction in catalyst loading lowered costs of the PEFC system significantly. Today the bipolar plates constitute a major contribution to PEFC stack cost, usually demanding around half the material expenses [2]. To be commercially viable, the cost of a PEFC system will have to be reduced substantially for most applications. Two applications where overall system cost is very important are residential power and automotive propulsion systems. The latter is especially demanding in competition with the internal combustion engine (US$ <50/kW) [3]. This entails that stringent cost targets be met for every material, component and manufacturing step involved in the PEFC system production. The near-term commercialisation of this technology has shifted the demand for equipment in the fuel cell laboratories from single cell test-stations to kW-range high cost stack test facilities. Similarly, there will be an increasing demand for lightweight and reliable fuel cell stack monitoring systems that are cost-effective and useful in commercial products. This paper presents and discusses possible ways to measure cell voltages on a high voltage stack, and describes a low cost prototype device designed, built and tested in our laboratory. The device is also suitable for monitoring battery systems but this paper focuses on fuel cell applications.

2. The need and requirements for stack monitoring systems

Despite the rapid and substantial PEFC technology development over the last decade, there are still several crucial operation parameters that need to be controlled. These relate to water management, fuel and air supply, temperature and pressure, etc. Based on this fact, one may argue that PEFC technology is still not mature. Fuel cell systems designed for transient operation need a monitoring system that provides information to complex control systems in order to (i) assure stable performance and efficient operation, (ii) protect the fuel cell from potential threats in the form of impurities and (iii) satisfy new safety requirements encountered when utilising alternative fuels like hydrogen.

An example of the latter is that an individual cell voltage drop is often the first indicator of a "burn-through," or a loss of separation between the hydrogen and air in the stack.

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Early detection in case of such an event is crucial to prevent serious and costly material damage.

When experimenting with a single fuel cell, the condition of the cell is usually determined by measuring the cell voltage and current, supplemented by a technique to obtain ohmic cell resistance, e.g. current interruption, ac impedance spectroscopy [4] or the fast auxiliary current pulse technique [5]. However, when working with fuel cell stacks, measuring stack voltage and stack current is not enough to ensure that all the cells are operating optimally. Cell current and individual cell voltages are the best indicators for evaluation of fuel cell stack performance. The cell current is the same for all cells but cell voltages may vary throughout the stack. For the PEFC variations in major operation parameters, such as local humidity, catalyst activity and temperature give rise to voltage changes. Membrane dehydration will give increased cell resistance shown as a reduction in cell voltage. Water accumulation (“flooding”) in a cell will reduce the active reaction area and because the cell current is ‘fixed’, the cell voltage will drop correspondingly. Catalyst poisoning (e.g. by CO) will have the same effect through reduction of the number of active reaction sites.

At high current density, the voltage of some cells may fall considerably lower than the average in the stack, e.g. from membrane dehydration. This causes more heat dissipation in these cells, exacerbating the problem. In the worst-case, some cells might be driven into reversal (<0 V). Experience from our work with PEFCs shows that only a few seconds in reversal will do permanent damage to the membrane-electrode assembly (MEA). To protect against cell reversal, the voltage of individual cells or small groups of cells must be measured. Stack manufacturer Energy Partners L.C. (FL, USA) monitors groups of cells (either two, four or even five cells) in stacks in some of their vehicles [6]. A low cost device for monitoring individual cell voltages could potentially find a use in commercial fuel cell systems. By measuring cells continuously, an on-board computer could automatically reduce the load or shut down the system. In a fuel cell car the device could trigger a ‘low cell voltage’ light analogous to the low oil pressure warning light in today’s combustion engine cars.

PEFC stacks consist of typically 50–100 cells. Because each cell may operate differently from the next, the need for individual cell voltage measurements is evident. By monitoring each cell, operation difficulties may be identified at an early stage and the control system can be triggered to undertake the required action and re-establish stable operation. In the case of stack failure, the monitoring system will be helpful in localising the problem and may also provide valuable information about the cause of the failure.

In addition to being low cost and compact, there are certain requirements for such a device related to accurate operation and reliability under realistic operation conditions.

- Operation temperature: −40 to +50°C.
- Measuring speed: 1–4 Hz (each cell) [7].
- Accuracy (±10 mV).
- Shock resistant.

3. Evaluation of concepts

Since, it is not reasonable to build a separate voltage measuring device for each cell in a large stack, the obvious way to measure the cell voltages is to send all the voltage signals to a multiplexer which selects one signal at a time to send to the voltage measuring device. Since, standard integrated circuit analogue multiplexer chips can only handle common-mode input signals up to around 44 V, measuring voltages directly is not feasible for a fuel cell stack of more than around 45 cells. PEFC-stacks, however, typically comprise 50–100 cells and hence give output voltages up to 50–100 V. Further, current off-the shelf high voltage multiplexers are generally very expensive, heavy, and voluminous.

3.1. Multiplexer configurations and accuracy

Three possible ways to measure a high voltage signal from larger stacks are shown in Figs. 1–3. A fourth method is discussed briefly. To illustrate the different methods, each figure shows a circuit with only two channels, which is sufficient to measure the voltage of one cell in the stack. In the figures, simple switch symbols are used to represent part of an integrated circuit analogue multiplexer. Throughout this paper “ground” is defined as the lowest voltage in the stack: the negative current collector (i.e. the anode side of the cell operating at the lowest voltage).

The highest voltage rating for off the shelf 0.1% accuracy resistors is typically 200 V. When a resistor is rated as “0.1% tolerance” this means “±0.1% of listed value”, so the worst-case error is 0.2% when looking at the difference between two resistors.

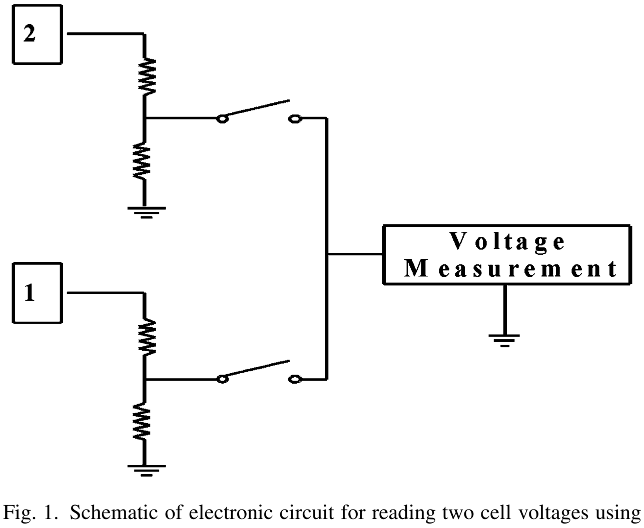

Fig. 1. Schematic of electronic circuit for reading two cell voltages using the voltage divider method.

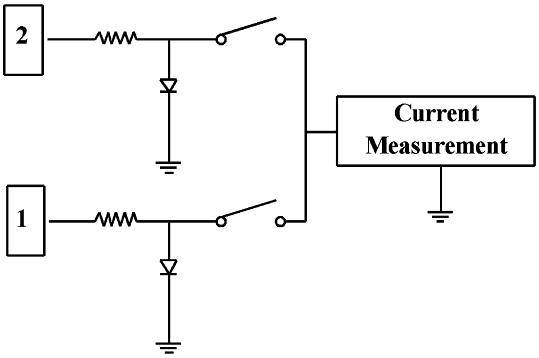

Fig. 2. Schematic of electronic circuit for reading two cell voltages using the resistor–diode method.

3.1.1. Voltage divider method

The voltage divider circuit in Fig. 1 simply divides the signal voltages to a level that a standard integrated circuit multiplexer can handle. The output from the multiplexer is a voltage that is measured by an analogue to digital (A/D)-converter. The maximum input signal voltage for this voltage divider method is the maximum voltage rating of the divider resistors. The worst-case error when measuring a cell voltage using the voltage divider method, E_{vd}, is given by Eq. (1)

$$E_{\mathrm{vd}} = 4tS \tag{1}$$

where t is the resistor tolerance, and S the cell voltage above stack ground.

Note that this is an approximation that is very good when the division ratio is high, such as 1:10. The implementation of this method is patented by Becker-Irvin [8].

3.1.2. Resistor–diode method

The second circuit shown in Fig. 2 uses a current switching method. When a channel is 'off', the voltage at the input to the IC multiplexer rises until it turns on the protection diode (about 0.6 V). The IC input voltage is then limited to one diode drop above ground and the rest of the voltage drop is shouldered by the resistor. When a channel is 'on', there is an extremely low impedance path to ground (besides the resistor), so the voltage at the input to the IC is essentially zero. This prevents the diode from turning on, and no current flows through the protection diode. The current from the output of the multiplexer is then measured with a low impedance current measuring circuit. The maximum input signal voltage for this resistor–diode method is the maximum voltage rating of the resistor. The worst-case error for the resistor–diode circuit, E_{rd}, is given by Eq. (2),

$$E_{\mathrm{rd}} = 2tS \tag{2}$$

which is half the error of the voltage divider method for the same resistor tolerance.

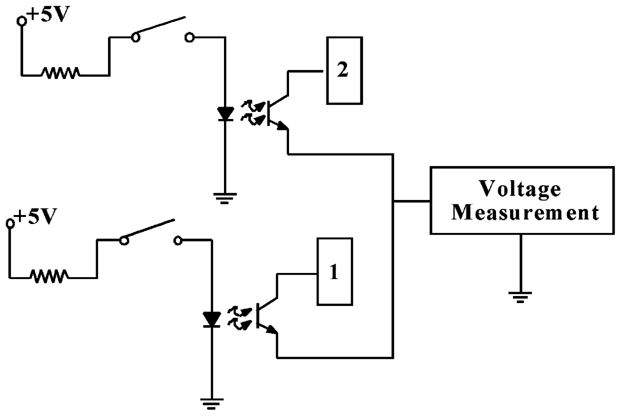

Fig. 3. Schematic of electronic circuit for reading two cell voltages using the optical isolator method.

3.1.3. Optical isolator method

The circuit in Fig. 3 uses an optical isolator to switch the voltage. This method is fundamentally different from the other two methods because a semiconductor device (the optical isolator) handles the high voltage, instead of a resistor. This will only work with an optical isolator because the gate of the transistor must be floating at a high voltage. The maximum signal voltage for this optical isolator method is the maximum voltage rating of the optical isolator. The highest voltage rating for off-the-shelf optical isolators is typically 350 V. The error of this circuit is not straightforward to analyse. The main error is the variation in transistor collector to emitter saturation voltage, which is not specified on the data sheets for optical isolators. Secondly, the transistor's saturation voltage depends in a highly non-linear way on the transistor current. Finally, each channel has a small but important leakage current when off, which depends in a slightly non-linear way on the transistor voltage. Thus, an error analysis is not easily performed for this multiplexer method.

3.1.4. Isolated amplifier method

The fourth method to measure cell voltages at high stack voltage incorporates an isolated differential amplifier, such as the Analog Devices AD102.[1] The isolated differential amplifier is used the same way as an ordinary laboratory differential amplifier, except that the input is electrically isolated from the output. This allows the input to float at very high voltages relative to the output without causing damage to the amplifier. Using this method, the cell voltage is measured directly and the signal is then translated to ground using transformer coupling. This circuit is straightforward, and is shown in the AD102 datasheet. This method was used in the Virginia Tech Hybrid Vehicle Program [9]. The error for this circuit is simply the specified error for the isolation amplifier. For the case of the Analog Devices AD102, the unity gain error is specified as ±5% maximum, and ±0.5%

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[1] Technical datasheet available at web address: http://www.analog.com.

typical. While ±5% error is much too high for this application, the error using this method is said to be around ±1% in practice [9].

3.2. Preferred multiplexer design

Of the concepts discussed above, the isolated amplifier method was ruled out because of the high cost of isolated amplifiers (US$ >25 per channel). Although the optical isolator method is potentially very accurate, it was not studied because the error was not well-defined. From the two remaining options, the resistor–diode method was chosen because of the inherently lower error and lower cost of this method over the voltage divider method.

4. Prototype device description

4.1. Physical construction

The prototype device was based on the resistor–diode method because of its reasonable and predictable error and very low cost. The prototype is a modular design with nine separate 7.5 cm × 11.5 cm printed circuit boards. The circuit boards are separated by function: power, micro-controller, main amplifier, channel bank selector, and five channel banks. Each channel bank has 16 channels, giving a total of 80 channels. The boards were interconnected using DIP plugs and ribbon cable. The device easily fits in a box with the dimensions 12.7 cm × 15.2 cm × 22.9 cm and weighs <0.5 kg. The size might easily be reduced to 7 cm × 7 cm × 10 cm, which will be the dimensions of the next version of the device.

4.2. Micro-controller and data acquisition

The micro-controller board is a SBC-8k from LDG Electronics.[2] It is based on the Motorola 68HC11 micro-controller. The micro-controller program was written in C and compiled using the ICC11 compiler from ImageCraft, Inc.[3] The tasks of the micro-controller include switching channels (using a MAX306 analogue multiplexer from Maxim for each group of 16 channels), controlling the analogue to digital converter (the 12-bit LTC1292 from Linear Technology), performing error correction and averaging calculations, and communicating with a Macintosh computer via RS-232 serial port. A driver for data acquisition, handling and on screen presentation of data was written in the software program LabView® (National Instruments), including emergency measures to shut down the stack in case of cell reversal. The voltage reference for the A/D converter was the LT1027 from Linear Technology.

4.3. Error correction

4.3.1. Resistor tolerance error

The resistor tolerance error for the resistor–diode method was given by Eq. (2). When uncorrected, this error is too high for the device to be suitable for a large stack. To calibrate the device, a high voltage power supply was set up to create two voltages. In the hypothetical example case below, the voltages are chosen to be 59 and 60 V. During calibration, all reference voltages were measured using a HP 34401A multimeter. The example (Table 1) shows the worst possible relative error for 0.1% tolerance resistors, with channel 59 being 0.1% to high and channel 60 being 0.1% too low. There is only one resistance affecting the channel, so the current is the voltage divided by the resistance of the resistor for that channel. The difference current is the difference in current between the two channels being measured. This difference is then multiplied by the resistor value to obtain the uncorrected voltage difference.

The offset voltage determined by the calibration in Table 1 does not depend on the voltage difference between the two channels but does depend on the common-mode voltage of the channels. Fortunately, this relationship is a simple linear one where any new offset is calculated according to Eq. (3)

$$V_{\text{offset,new}} = \frac{V_{\text{common mode,new}}}{V_{\text{common mode,calibration}}} V_{\text{offset,calibration}} \tag{3}$$

Correcting the readings by applying Eq. (3) gives a small error when (i) the differential voltage is much smaller than the common-mode voltage, or (ii) the common-mode voltage is low. One of these two cases always applies when measuring cell voltages in a fuel cell stack. Table 2 shows the calibrated channels after the stack conditions are changed to a significantly lower operating voltage.

Early prototype calibrations were performed as shown in the example above. An easier way to calibrate the device in practice is to connect all of the channels to a single high voltage power supply. Since, all the channels are connected, the correct differential voltage is known, as is the common-mode voltage. In this way, each group of 16 channels could be calibrated in a few seconds. This method was found to work as well in practice as the original method of using different calibration voltages for each channel.

4.3.2. Voltage coefficient error

For some resistors, the voltage coefficient (change in resistance versus change in applied voltage) could add significant error. The voltage coefficient for the resistors used in the prototype device was not given in the data sheet. However, in many data sheets where voltage coefficient is given, it is lower than other errors, such as resistance tolerance and temperature coefficient. Therefore, this error was assumed to be negligible because additional errors observed during testing were much lower than the tolerance error.

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[2] Web address: http://www.ldgelectronics.com.

[3] Web address: http://www.imagecraft.com.

Table 1
Device conditions during calibration

Channel number	Voltage (V)	Resistance (MΩ)	Channel current (mA)	Difference current (A)	Uncorrected voltage (V)	Calibration offset (V)
59	59	1.001	5.8941×10^{-2}	1.1190×10^{-6}	1.1190	0.1190
60	60	0.999	6.0060×10^{-2}			

4.3.3. *Temperature coefficient error*

Another error imposed by temperature changes in the device was not corrected. This error would, however, be important in many practical applications and is caused by the temperature coefficient of the resistance (TCR). The resistors applied in the present device have absolute TCR of up to ±25 ppm/°C. For a temperature range of ±30°C from the calibration temperature, this would add a maximum error of ±15% at a common-mode voltage of 100 V. Introduction of a temperature sensor in the device would facilitate a satisfactory temperature correction. The error could then be corrected similarly to the resistor tolerance error, taking into account the non-linear behaviour of the TCR. Another option (and possibly a more cost-effective solution) would be to use resistors with better temperature characteristics. Several manufacturers produce resistors with TCR of <±5 ppm/°C, which would add <6% to the error for the above case. An example is the TSP series of thin film resistor networks from Vishay, with relative tolerance within a network better than 0.1%, and relative TCR better than 2 ppm/°C. The prototype device was both calibrated and operated at room temperature, so the temperature coefficient error was not detected.

4.3.4. *Noise error*

Electrical noise caused a significant error in the prototype device. Single measurements from the device had a standard deviation of around 70 mV. To correct this error multiple measurements were averaged. Averaging 10 voltage readings per cell on the computer, the system can read 60 cells/s with a S.D. of 5 mV. Adding internal instrument averaging of 8 voltage readings per cell, the system can read 19 cells/s with a S.D. of 1.5 mV. Because the error continues to decrease as the number of repeat measurements increases, we assume that this error is random. We also expect this error could be greatly reduced by improving the circuit design using low-noise techniques.

4.3.5. *Total error of prototype device in use*

The errors that are corrected are the relative tolerance error and the noise error. All other errors are assumed to be smaller than these errors and are not corrected. During testing it was found that the device measured differential voltages within ±30 mV of the HP 34401 A at common-mode voltages of up to 80 V. From this moderate error we can conclude that the most significant errors for our operating conditions are in fact the tolerance error and the noise error. For applications experiencing a wide range of operating temperatures, the TCR error would become important, requiring introduction of a temperature sensor and corresponding temperature correction or the use of more expensive precision resistors.

5. Results and discussion

5.1. *Prototype device performance*

The prototype is currently in use on small PEFC stacks of up to 26 cells at Los Alamos National Laboratory, NM, USA. The prototype has 80 channels and is limited to 200 V. The device has been tested for speed and accuracy. The voltage readings may be averaged both in the instrument's micro-controller and in the computer. There is, as usual, a trade-off between speed and accuracy. Averaging 10 voltage readings per cell on the computer, the system can read 60 cells/s with a S.D. of 5 mV. Adding internal instrument averaging of 8 voltage readings per cell, the system can read 19 cells/s with a S.D. of 1.5 mV.

One of the main features of the device is protecting individual cells in the stack from low cell voltages. Two voltage limits were applied, one warning voltage (typically 300 mV) and one stack shut down voltage (typically 0 mV). To respond quickly to rapidly falling voltages, high sampling speed and fast data transfer to the computer is crucial. Every reading from the device was immediately compared to the warning voltage limit before averaging to improve response time. Any voltage falling below the warning voltage limit was then compared to the stack shut-down voltage, and the procedures triggered accordingly.

The speed (60 cells/s) of the device was high enough to protect fuel cell stacks of up to 100 cells against damages

Table 2
Data for calibrated channels at cell voltages of around 30 V

Channel number	Voltage (V)	Resistance (MΩ)	Channel current (mA)	Difference current (mA)	Calibration offset (V)	Corrected voltage (V)
59	30	1.001	2.9970×10^{-2}	5.6050×10^{-4}	0.0605	0.500
60	30.5	0.999	3.0531×10^{-2}			

caused by low cell voltage, when conservative values were chosen for the warning/shut down limits. The accuracy (±5 mV) was also satisfactory for stack protection purposes. The next version of the device will be improved and use motherboard design and a higher resolution A/D converter. The material cost of the prototype was in the range of US$ 400–500, but the device could probably be mass-produced for less than US$ 200.

The prototype device was connected to a computer via RS232 and the software program LabView handles communication and displays the results on screen.

5.2. Prototype device costs

For cost estimation, the system is divided into two parts. The first is the multiplexer side of the device, which includes the parts that increase system cost with each additional channel. An estimation of costs for this part of the system is shown as Table 3. The parts that are the same regardless of the number of channels are shown in Table 4. Note that these costs are for the prototype device. Costs for mass-produced devices could be substantially reduced, especially for the micro-controller and printed circuit board costs.

5.3. Useful for stack design

Monitoring individual cell voltages is valuable for more than protecting the stack from permanent damage during operation. It may also be useful during the fuel cell stack design phase, where problems associated with (i) stack water management, (ii) temperature distribution, (iii) gas distribution and (iv) inert gas accumulation are typically encountered. Monitoring individual cell voltages during stack testing may give valuable information about processes (e.g. cell dehydration, reaction gas depletion, etc.) occurring at the single cell level. Some processes of interest have a much shorter time window than what is possible to measure with the prototype described above. This includes studying ohmic resistance of individual cells in a fuel cell stack. The current interruption technique is only viable for small lab scale cells and under certain conditions [10], whereas for higher currents this method encounters difficulties related to the inductance of the dc-current loop. Hence, ac impedance spectroscopy [4] or the fast auxiliary current pulse technique [5] is preferred for stack applications. For studying ohmic resistance of individual cells, a very high sampling speed is needed.

Table 3
Estimated per-channel costs

Part	Cost per cell (US$)	Total cost for 80 cells (US$)
Channel resistor	1	80
Channel diode	0.30	24
Analog multiplexer	0.65	52
Circuit board/construction	1.50	120
Total	3.45	276

Table 4
Estimated fixed costs

Part	Cost (US$)
Micro-controller	80
A/D converter	20
Voltage reference	10
RS232 interface	5
Current measurement circuit	20
Circuit board and construction	75
Total	210

6. Conclusion

There are different systems available for monitoring individual cell voltages in fuel cell stacks covering a wide range of accuracy and speed. Faster systems may be used for advanced studies of fuel cell stacks, such as technology development and optimisation. Such systems suffer from high cost, volume and weight. A system for stack protection against cell reversal does not have the same strict requirements for speed and accuracy; hence a slower and cheaper system may be used. There is every indication that fuel cells will find large-scale application in vehicle propulsion. A cell voltage-monitoring device will constitute an integral part of a fuel cell stack control system. For mass production, none of the existing technologies are viable, either due to price or volume or both. The device developed, built and tested at Los Alamos National Laboratory, NM, USA will potentially be low cost, but still accurate enough to meet the requirements of a fuel cell system for use in transportation applications.

Acknowledgements

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