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Analysis of Cell to Cell Voltage Variations in a 4-cell and 25- Cell Low Temperature PEM Stacks

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Abstract. An experimental study of cell to cell voltage variations on two different low temperature (LT) PEM stacks is presented. One is a-4 cell-membrane-humidified stack. The second is a-25 cell stack with an external humidifier. The test results taken from open circuit voltage to full load reveal that in both stacks, the first cell almost always produced the least voltage. Further tests at additional two levels of air stoichiometry (S_{air}) with the 4-cell stack confirmed the previous observations. An analysis is conducted to unravel the influence of various factors on cell to cell voltage variations. Limitations of this investigation are noted and future work is suggested.

Keywords. Cell to cell voltage variations, Low temperature PEM, SERC-4 and Ballard 25 cell stacks.

1. Introduction

A study is conducted on two different low temperature stacks to unravel the causes of cell to cell voltage variations under steady-state test condition using two different test equipment. The observation of cell to cell voltage variations in stacks has been indirectly reported by some researchers whose work was based on simulations [1]. Various justifications for cell to cell variations (ctcv) have been reported in literature [2, 3, 4, 5, 6]. The variations are attributed to the stack design, flow direction (co-flow and contra flow) and manifolding of the stack. Voltage variation presents a complex problem to unravel because of flow field design, fluid mechanics of flow, non-uniformity of reactants in each cell, reactant stoichiometry, etc. The authors adopted an experimental approach to find the common causes of this phenomena in two different stacks. The discussion that will follow this report and the conclusions will stimulate future studies in this phenomenon.

The phenomenon of voltage variations in a stack generates a serious interest of studies. A literature survey based on the cited work above shows that for a successful design and operation of a PEM fuel cell stack, the uniformity of oxidant and fuel in each cell of the stack has to be maintained. The humidification level has to be optimal. The difference in temperature within cells has to be infinitesimal. The loss of reactants due to leaks must be eliminated or minimized. This can be done through careful design and assembly. A careful approach to stack assembly will eliminate leaks and contact resistance. Various stack flow distributions are presented in literature. Most common ones are: the U-tube with stack inlet and outlet in opposed directions and the Z-type with the flow inlet and exit in same direction. Another dimension of this design includes the co-and counter flow [6] in which both reactants' streams and coolant streams are in the same direction (co-flow). In the counter-flow design, the fuel stream is in the opposite direction to the coolant and oxidant flows. The choice here is based on how well the stack handles humidification issues in the stack.

The merits of a co-flow are the temperature gradient on the anode and cathode sides of the stack remain relatively constant and the tendency to flooding of the stack is significantly reduced. The demerits are the risks of the stack reactants' inlet being dry and hence, jeopardizing the life of the stack. The counter flow, on the other hand improves humidification. This is due to water –laden exhaust water which crosses over to the anode side [6]. However, counter-flow is identified as having a hot fuel-in at one end of the stack and cold fuel-out at the cold end of the stack. This condition reduces condensation. A comparison of both arrangements shows insignificant difference in the stack performance.

Other design factors contribute to vtvv such as anode and cathode pressure. Increased pressure leads to improved stack performance. Hydrogen and oxidant partial pressure contribute to the increased performance. It is strongly recommended that the anode pressure be greater than the [6] cathode pressure to reduce nitrogen crossover. The crossover contributes to cell stack instability.

One of the basic requirements of the fuel cell stack is that it should supply the required potential for a specific operation. The stack voltage is often the sum of the voltages of all the cells in a series connection. A careful look at individual cell potential shows that, there is a cell to cell variation which can be substantially argued to be a combination of various factors summarized above. For the voltage of each cell to be same or nearly the same, there must be an even distribution of reactants in each cell and, the flow rate has to be kept the same which can be difficult at high loads and flooding conditions.

Design parameters impact flow distribution in the channels especially for multi-cell stacks ($n>6$), where n is the number of cells in the stack. Cells located far from the inlet port are found to be impacted by possibly flow travel distance and non-distribution of reactants especially at higher current densities. At this condition, the cell generates a lot of water, some of which accumulates in the channels and this can lead to increased mass transport polarization. These research findings are simulation based [3]. There are no experimental reports to correlate their findings. These works were carried out on the widely used parallel flow channels and single serpentine channels configurations. The inlet port was located mid-way between the bipolar plate (BP) length. The position of the inlet port also impacts some outcomes. Studies with multi-serpentine configuration are credited with uniformity of flow by virtue of its parallel channels.

2. Experimental set up and test matrix

The 4-cell stack (SERC-140) has an inbuilt membrane humidifier on the cathode side with 4 humidification cells. The stack has a total area of 140 cm^2. The stack's 4^{th} cell is nearer to the humidifier. In the entire setup, only the cathode reactant is humidified, the anode side is not. The SERC-140 stack was tested from OCV to 60A at three levels of air stoichiometry (200, 300 and 400%). The operating temperature was set to 60 ^oC. The SERC test station 2 used has a maximum power capacity of 200 Watts, a maximum hydrogen pressure of 5 psig (34.47 kPa), maximum air flow of 0-200 slpm. Hydrogen flow mode is dead-ended.

The test equipment incorporates seven integrated sub-systems (i) air (ii) hydrogen (iii) water - coolant is used for heat removal (iv) electrical system – consisting of AC and DC systems. The fuel cell power is absorbed by an electronic load. The remaining three sub-systems are: (v) computer monitoring system. The test bench incorporates four test stations on one bench. A single computer controls all four stations, which serves for monitoring, data collection and operation. A sixth (vi) is software subsystem using a LabView interface; and finally – (vii) the Safety Controls. The picture of the SERC-140 stack is presented below.

In the 12 cell stack, both air and hydrogen are humidified. The commercial Ballard Mark 9 SSL ^{TM} used is mounted on a Greenlight Test station. The 25-cell stack was tested from OCV to a maximum load of 300A. The custom settings for testing on a GreenLight test equipment were applied. At each test procedure, adequate time of not less than five minutes was allowed for the stack to attain steady state conditions before readings were made. Cell to cell voltages were recorded including maximum and minimum cell performances and their locations within the stack. For brevity reasons, only reports of cells 1, 5, 10,15,20 and 25 cells will be presented here for the 25-cell stack.

3. Analysis of the report

3.1. SERC-140.

A test on the four cell stack was conducted from OCV to a maximum load of 60 Amps. Three levels of air stoichiometry were investigated. The aim was to unravel the impact of stoichiometry on voltage to voltage variation in this stack. The limited data (for brevity reasons) shown on Table 1, and the full data plotted in Figures 1-3 present the following findings: (i) Each successive cell from Cell # 1, 2, 3 and 4 in that order of progression showed voltage increase up to 8Amps. Meaning, cell #2 has a higher voltage than cell #1 at any load setting, etc. Thereafter, after 8 amps, cell #4 output falls below cell #3, while cells 2>1, 3>2 continued to increase with a new load setting. Also, at higher loads, the magnitude of cell to cell variation diminished. The flow rates streamlined. The best performance was obtained at S_{air} =3. Finally, it was observed that cell to cell variation depends on air stoichiometry, S_{air}. The test stand used, in this case is dead-ended. The hardware for this test is shown in Figure 1(a &b). The data given in Table 1 (a,b,c) is for a quick review. A complete data set consisted of test runs from OCV through 2 amps interval to 14 amps and thereafter from 15- 60 amps through 5amps interval.

Figure 1(a) the air side of the SERC -140 stack

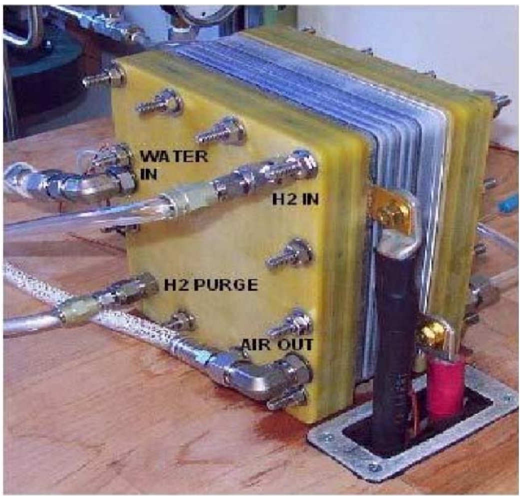

Figure 1(b) the hydrogen side

Table 1. Experimental data on SERC-140 stack at 200, 300 and 400 % air stoichiometry

(a) Stoichiometry, S_{air} = 200%

Load (A)	V1 (V)	V2 (V)	V3 (V)	V4 (V)
0	791	808	821	912
10	733	748	763	769
20	703	718	736	733
30	683	695	714	706
40	663	673	695	684
50	644	650	674	663
60	634	635	658	646

(b) Stoichiometry, S_{air} = 300%

Load (A)	V1 (V)	V2 (V)	V3 (V)	V4 (V)
0	815	836	849	937
10	761	776	790	787
20	726	740	754	748
30	699	710	727	717
40	674	685	703	692
50	661	665	683	672
60	645	646	665	654

(c) Stoichiometry, S_{air} = 400%

Load (A)	V1 (V)	V2 (V)	V3 (V)	V4 (V)
0	808	840	857	938
10	760	778	790	787
20	723	741	756	748
30	697	712	729	719
40	683	690	704	696
50	665	670	687	675
60	648	651	667	657

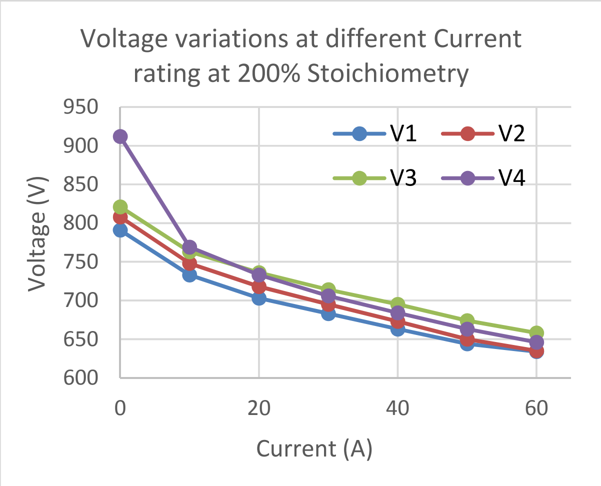

Figure 2. Cell voltage variation from OCV- 60A load for the 4 cell stack at 200% air Stoichiometry

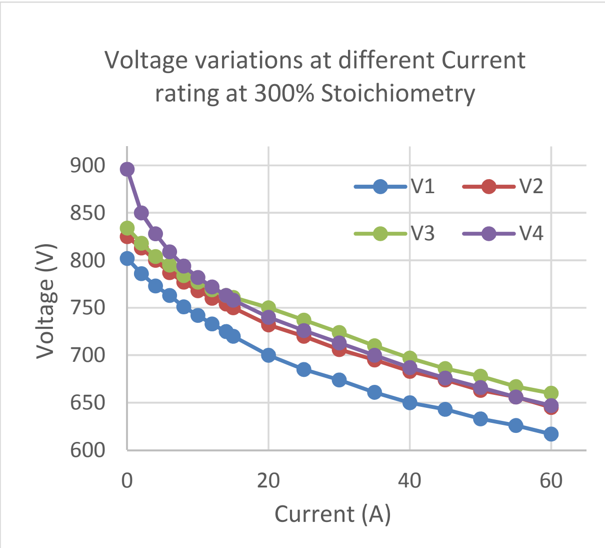

Figure 3. Cell voltage variation from OCV- 60A load for the 4 cell stack at 300% air Stoichiometry

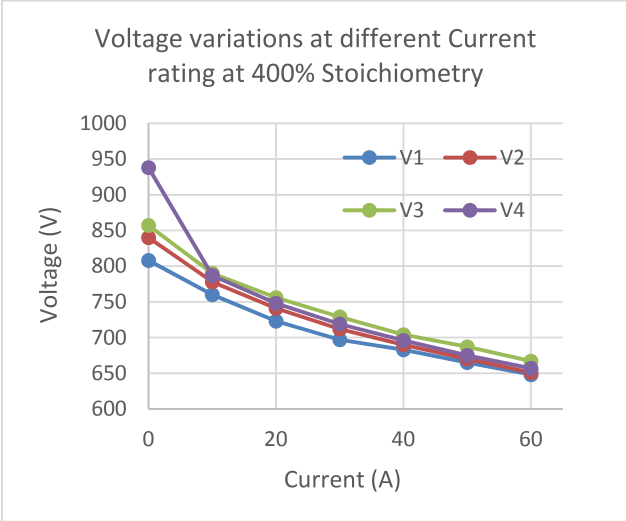

Figure 4. Cell voltage variation from OCV- 60A load for the 4 cell stack at 400% air Stoichiometry

3.2 Ballard Mark 9 SSL ™ 12- cell stack

The analysis of the 12- cell stack unravels the nature of voltage variation in Ballard stack. The Ballard 12 cell stack was tested from OCV, 15, 30, 60, 120, 200 to 300 Amps. The results are presented in Table 2 for each of the six test runs. The test matrix and the main basic values are listed in Table 2. Other parameters of interest are: the stack voltage (V_{st}); stack current (A_{st}); stack power Pe_{st}); cells average voltage (CV_{avg}); The standard deviation of the cells (V_{sd}) in each test run was found to be 0.01 throughout, while the cell minimum voltage CV_{min} gives an idea of its deviation from the cell average. The value ranged from 0.03V at OCV to 0.01 - 0.02 amps from 15 – 300 amps.

Table 2 Experimental data for Ballard Mark 9^{TM}

Varia ble	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Load [A]	0	15	30	60	120	200	300
Vst [V]	22.9	20.4	19.5	19	17.9	16.7	15
Pe [W]	0	301. 3	580. 2	1137. 8	2137. 4	333 0.6	4498
CV_{avg}	0.92	.82	0.78	0.76	0.72	0.67	0.6
CV_{sd}	0.01	0.01	0.01	0.01	0.01	0.01	0.01
CV_{min}	0.89	0.8	0.76	0.74	0.7	0.66	0.58

Analysis of the result shows that cell number one generated the least voltage at all the six loads and OCV tested except at 120 Amps while cell #5 exhibited the highest voltage. Figures 5-11 present graphical representations of six selected cells in the stack. The selection was based on uniqueness of the variation of cell voltages. At OCV and 15 Amps (runs 1 and 2), cells 5, 15, 25 generated the highest voltages. (with Cell #5 as the highest of the 3), followed by cell 10. Similar observations for other loads are listed in Table 3.

Table 3. Select cells with the highest voltages at OCV- 300 amps.

Load Amps	Voltages	*Cells #s	
OCV		5, 15, 25	
15A		5,15,25	
30 A		5,10,15,25	
60 A		15,10,5,25	
120A		5,15,25,10	
200A		15,25,5	
300A		15,25,5,10	

- The highest voltages in a descending order at each load is presented

A careful examination of the results reveals that Mark 9 is very well designed and assembled. Cell to cell variation at each test run has a standard deviation S_d of 0.01. The difference between average voltage and minimum cell The constancy of voltage to voltage variation of runs, between CV_{min} and CV_{avg} (of 0.01-0.02V) from 15 amps to 300 amps is indicative of a highly engineered stack.

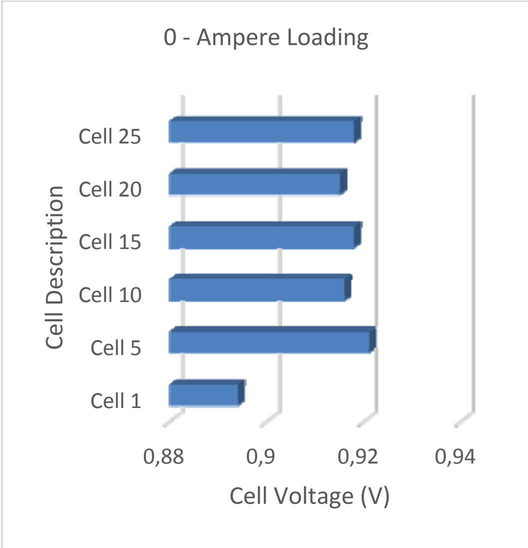

Figure 5. Ballard Mark 9^{TM} cell to cell variation at OCV.

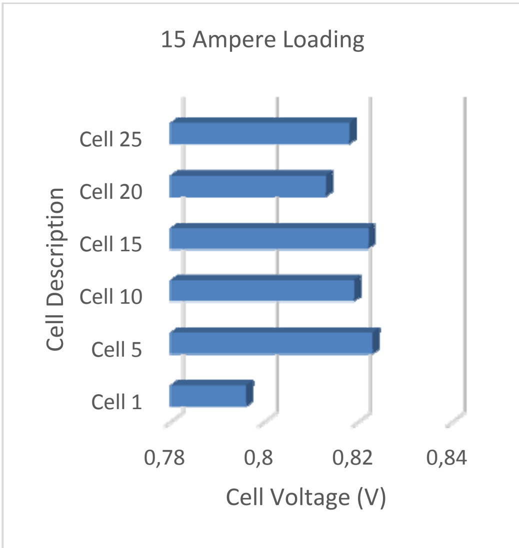

Figure 6. Ballard Mark 9^{TM} cell to cell variation at 15 amps.

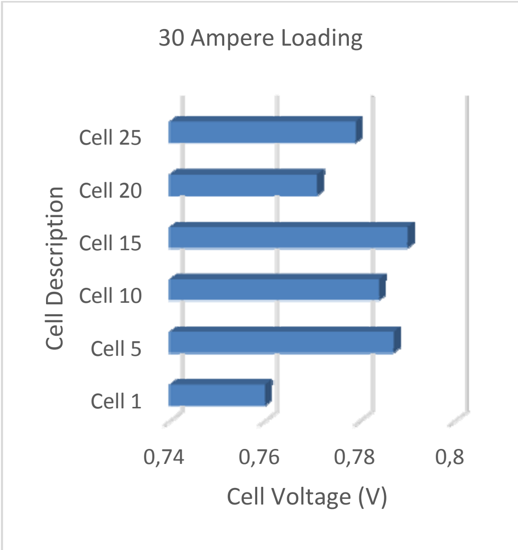

Figure 7. Ballard Mark 9™ cell to cell variation at 30 amps.

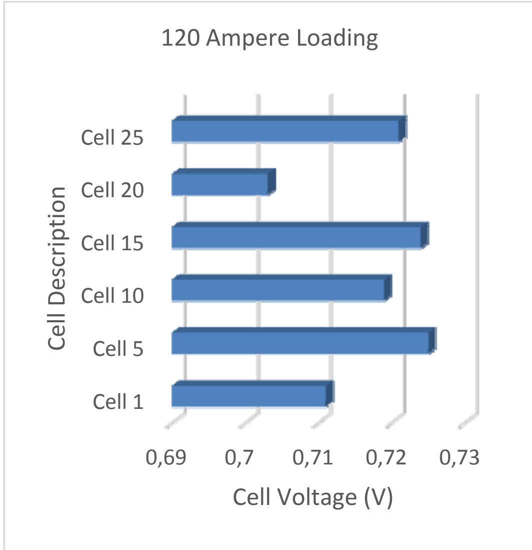

Figure 9. Ballard Mark 9™ cell to cell variation at 20 amps.

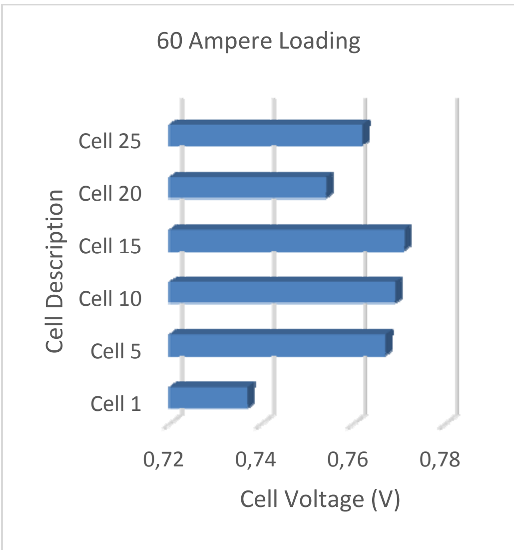

Figure 8. Ballard Mark 9™ cell to cell variation at 60 amps.

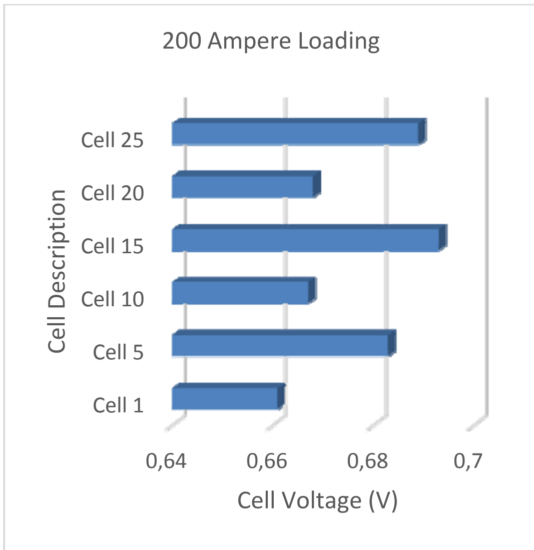

Figure 10. Ballard Mark 9™ cell to cell variation at 200 amps.

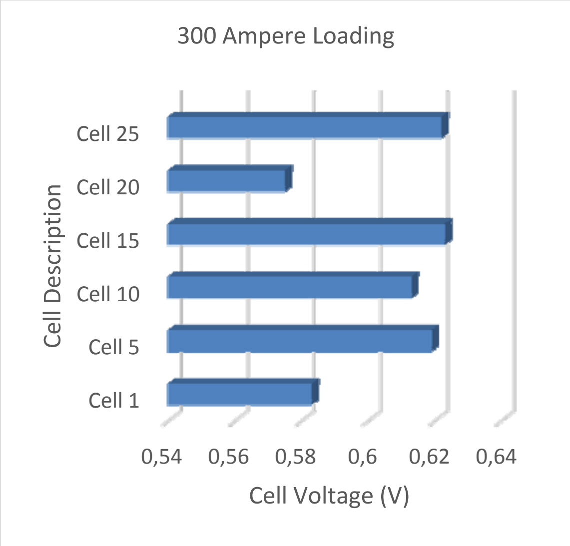

Figure 11. Ballard Mark 9™ cell to cell variation at 300 amps.

4. Conclusions

These are the concluding remarks for the test carried out so far on two dissimilar stacks and test equipment:

- Cell number one at all loads in both stacks generated the lowest voltage
- The fourth cell in SERC-140 stack developed the highest voltage up to 8 amps and then drops below its third cell value. Cell #3 produced the highest voltage for the remaining loads tested. For the 25 cell stack, its 5th,15th and 25th cells produced the highest voltages.
- This work is not conclusive. It requires further studies with more stacks and flow channel configurations to unravel the main and immediate causes of cell to cell voltage variations in large stacks.

5. References

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