Development of an Intelligent Battery Management System for Nickel-Hydrogen Satellite Battery

K.A. Akpado, C.C. Okezie and B.C. Idioha-Chidozie

Abstract— Battery power management in satellite systems continues to evolve with current research working to push the boundaries of depth of discharge and serviceable life further requiring new and intelligent techniques. Moving away from the high cost of human monitoring of battery systems, new and intelligent systems are now becoming mainstream such that battery management task is automated with reduced human influence or intervention. Fuzzy logic is here utilized for such automation and compared to the results obtained from a PID only control scheme. The advamtages were properly catalogued in terms of control energy and standard feedback resonse parameters like rise time, steady state, overshoot and error.

Index Terms— Battery Management, Charge Controller, Fuzzy Logic, Nickel-Hydrogen Battery , PID, Satellite Power System.

1 Introduction

As space technology continues to make inroads into more aspects of human life with direct applications in diverse areas of human endeavor, the need to properly manage onboard satellite systems becomes a prerogative to be met ().Aeroponics, communication, environment, economy, politics, security, education, health, agriculture are different specific areas that are impacted on a daily basis by satellite technology to name a few(). The need for continuity in data acquisition and collection becomes a given to be maintained through properly working onboard systems that are directly or indirectly fed by energy from the sun and stored energy in batteries(). Such charging. Storage and discharging cycles requires proper battery management which is driven by intelligent battery managemenrt schemes that are control driven(). Some examples of utilized batteries on satellites include: Lithium-Ion, Nickel-Hydrogen. These satellites missions range from Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Earth Orbit (GEO) missions, which make various energy demands on the satellite power management system and need to be continuously improved to get the optimum from any satellite mission in terms of long life, mission success, reliability .

In satellite power system applications, the Nickel-Hydrogen battery system has largely replaced the sealed Nickel-Cadmium technology that was widely and successfully used to power space systems from the early days of spaceflight (Albert H. Zimmerman 2003). A typical example of the advantages of Nickel-Hydrogen is provided by the Hubble Space Telescope, which has operated for more than 15 years on nickel-hydrogen batteries with limited battery degradation. These capabilities, when coupled with growing manufacturing and performance problems with spacecraft Nickel-Cadmium batteries in the mid-1980s, clearly pushed Nickel-Hydrogen batteries into space use. Nickel-hydrogen batteries when compared to other space batteries, has a couple of advantages; moderate weight, high life, high reliability, low cost, low size/volume and moderate safety (Albert H. Zimmerman 2003).

For such advantages to be fully harnessed, it is necessary therefore to provide a means to intelligently control the charge and discharge and overall health of the space batteries. Most space missions are currently being faced with the tendency of not being effectively achieved. This is because most power systems on the spacecrafts depend on continuous support from mission control. This is a major setback in the simulation of the EPS which is important in determining the sizes and capabilities of the solar arrays and the batteries to accomplish the mission objectives.

2 Review of Battery Management

Satellite power system which is also referred to as Electrical Power Subsystem of the satellite forms a core and critical subsystem of the satellite. It is used to power satellite systems by distributing electrical energy to the various parts of the satellite. It comprises of solar cells (which converts solar radiations to electrical energy when the satellite is illuminated by the sun) and rechargeable batteries that maintain power supply during solar eclipse. Figure 1 shows a typical schematic of the satellite power system

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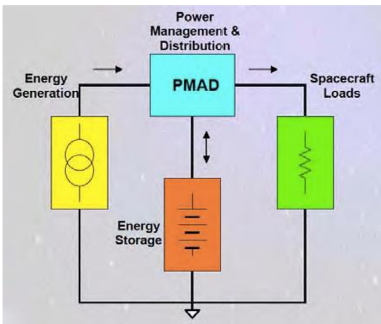

Fig.1. Typical Schematic of a Satellite Power System

Although the parts of Figure 1 are self explanatory, **Energy Generation** block comprises of the sun and solar cells/ array which converts incoming optical energy into electrical energy.

Power Management and Distribution block, depicts how the power generated is converted. It also takes care of the power control, charge/discharge control distribution of electric current to various systems and manages faults.

Energy Storage comprises mainly batteries which are electrochemical devices which generate electric current from a chemical reaction. Batteries are used on a spacecraft as a means of power storage. Batteries are divided into two types primary (contains all its usable energy and can only be discharged) and secondary (can be recharged from other source of energy) batteries.

Spacecraft Loads- this comprises of the various systems on board that will receive power.

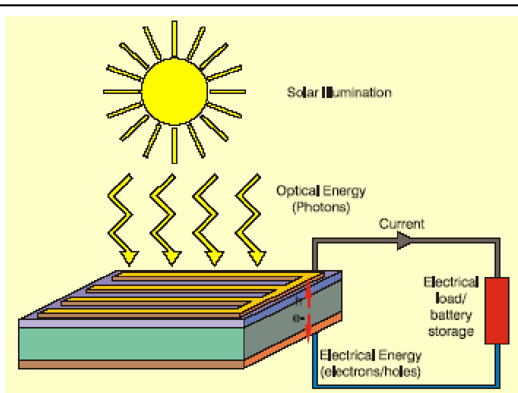

Fig. 2. Schematic of a Solar Cell Operation.

2.1 Review of Nickel Hydrogen Battery

The Nickel-Hydrogen battery cell is a rechargeable electrochemical cell that has found wide use in high-reliability space applications that require extended service life. These applications include satellites operating for 15 or more years in geosynchronous orbits, as well as orbital spacecraft (in low Earth orbits) that require many tens of thousands of charge and discharge cycles from the batteries. Nickel-Hydrogen technology was developed for space use beginning in the early 1970s as a spin-off of the hydrogen-oxygen regenerative fuel cell and is a technology capable of long life and high reliability without the periodic refueling and servicing needs typical of fuel cells. The Nickel-Hydrogen battery cell performs essentially as a quasi-reversible hydrogen-oxygen electrochemical cell, with the oxygen being stored in the positive electrode as a metastable nickel oxyhydroxide and the hydrogen being stored as high-pressure gas in a pressure vessel. The positive electrode was selected to be the highly reliable and robust nickel electrode that had been used for years in the nickel-cadmium cell. The energy storage reaction at the positive electrode can be represented by the simplified chemical reaction.

$$NiOOH+H_2O+e \Longrightarrow Ni(OH)_2+OH \quad (2.1)$$

The negative electrode is a catalyst-based gas electrode that has been largely developed and utilized in the fuel cell industry. This electrode electrochemically stores energy by the reaction in the form of hydrogen gas, which is contained in the cell container at high pressures.

$$1/2H_2+OH \Longrightarrow H_2O+e \quad (2.2)$$

The chemical representation of the overall reaction within the cell is given below

$$NiOOH+1/2H_2 \Longrightarrow Ni(OH)_2 \quad (2.3)$$

After more than 30 years of development and transformation, Nickel-Hydrogen technology has reached a point of key historical significance. While the technology is now the dominant rechargeable energy-storage system used in the space and satellite industry, support for further nickel-hydrogen cell development, system optimization, and technology maintenance is decreasing each year. Without a critical level of technology development or maintenance support, it

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frequently has been the case that even the most established battery technology can be compromised by erosion of production infrastructure and manufacturing expertise.

2.2 Review of Battery Control Techniques

To control the charge, storage and discharge cycle of the battery, several techniques have been highlited in literature and utilized in practice. Some of these techniques include: simple on-off control, traditional PID regulation, mixed or hybrid control techniques such as PID and Fuzzy, Fuzzy etc. However, detailed comparison of the techniques are sometimes not well documented and presented for practitioners in academia and industry to appreciate. This work seeks to make the benefits of fuzzy logic over PID control more comprehensible and further well documented.

2.3 Battery Dynamics

The battery models in use for simulation and control are obtained fromo either the equivalent circuit model (ECM) or the electrochemical or thermal model. The ECM is shown in Figure 3

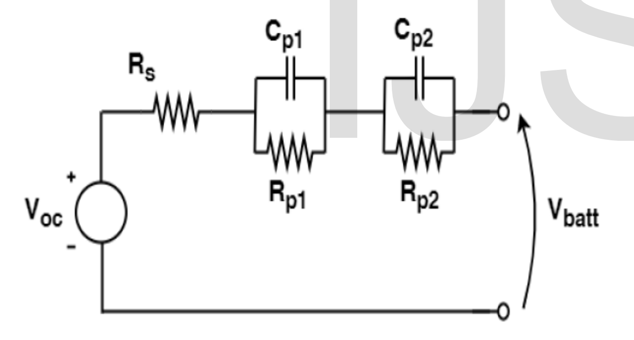


Fig. 3. Magnetization as a function of applied field. Note that "Fig." is abbreviated. There is a period after the figure number, followed by one space. It is good practice to briefly explain the significance of the figure in the caption.

This battery equivalent circuit yields the following set of equations

$$V_t = V_{OC} - R_s I_t \equiv V_{OC} - V_{p1} - V_{p2} - R_s I_t$$
$$\frac{dV_{p1}}{dt} = -\frac{V_{p1}}{\tau_{p1}} + \frac{I_t}{C_{p1}}$$
$$\frac{dV_{p2}}{dt} = -\frac{V_{p2}}{\tau_{p2}} + \frac{I_t}{C_{p2}}$$

The Battery model given by equation (1) represents the equivalent circuit model of a simplified battery system. From the equation we can see the following parameters: Battery terminal voltage (Vt), open circuit voltage (Voc), Vp1 and Vp2 represent different cells of the battery. Rs is the internal resistance of the battery and other parameters are similarly defined.

2.3.1 Thermal Balance

The thermal for the battery system is developed from the 1st law of thermodynamics given by

$$\frac{dU}{dt} = Qgen - Qloss$$

Where.

$$dU = m * Cp * dT_{cell}$$

The ohmic losses are given by

$$Qgen = R0 * I^2 + R1 * I_1^2$$

The convective and conductive losses form the loss of the battery

$$Qloss = Qconv + Qcond$$

These losses are characterized by

$$Q_{conv} \equiv h_{conv} * S_{area} * (T_{cell} - T_{air})$$
$$Q_{cond} = \frac{T_{cell2} - T_{cell1}}{R_{cond}}$$

In some literature, Qcond is ignored as the difference in temperature Tcell2-Tcell1 is negligible. Therefore, modifying equation () for dU/dt

$$mC_p \frac{dT_{cell}}{dt} = Qgen - Qloss$$

$$\frac{dT_{cell}}{dt} = \frac{Q_{gen} - Q_{loss}}{mC_p}$$

From which after substitutions of relevant expressions, the final form of the battery thermal model becomes

$$\frac{dT_{cell}}{dt} = \frac{(\mathrm{R_0 I^2 + R_1 I_1^2}) - h_{conv} S_{area} (T_{cell} - T_{air})}{mC_p}$$

The complete set of battery equations now becomes

$$V_t = V_{OC} - R_s I_t \equiv V_{OC} - V_{p1} - V_{p2} - R_s I_t$$
$$\frac{dV_{p1}}{dt} = -\frac{V_{p1}}{\tau_{p1}} + \frac{I_t}{C_{p1}}$$
$$\frac{dV_{p2}}{dt} = -\frac{V_{p2}}{\tau_{p2}} + \frac{I_t}{C_{p2}}$$
$$\frac{dT_{cell}}{dt} = \frac{(\mathrm{R_0 I^2 + R_1 I_1^2}) - h_{conv} S_{area} (T_{cell} - T_{air})}{mC_p}$$

Equation shows the battery ECM and nthermal model which are used for the simulations of open and closed loop battery management tests.

4 Methodology and Experiments

The experiments were conducted in simulation only and achieved with the aid of Matlab/Simulink 2018a. The following methodology was followed in the simulation experiments;

1. Development or adoption of the battery ECM
2. Development of an open loop test on the batter ECM
3. Development of closed loop test using a standard PID tuned with Matlab's PID tuner
4. Development of the FLC to replace the PID controller
5. Presentation and discussion of results

4.1 OPEN LOOP TESTS

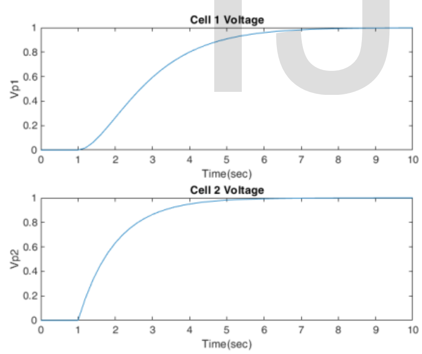


Fig. 4. Open loop test results for the output voltage of cells 1 & 2.

It is seen that cell one has a well pronounced second order response profile. Cell two is also second order but has a less pronounced profile. This is borne out of visually inspecting both plots and the inflection points on the graph

4.2 Closed loop Experiments

A first test for closed loop response was made on the battery ECM of Figure XX. This test utilized a PID controller which was initially NOT tuned.

Experiment	P	I	D
Untuned	1	1	0
Tuned	X	x	x

The PID response was obtained first without tuning and without any disturbance injected. Figure XX shows this response

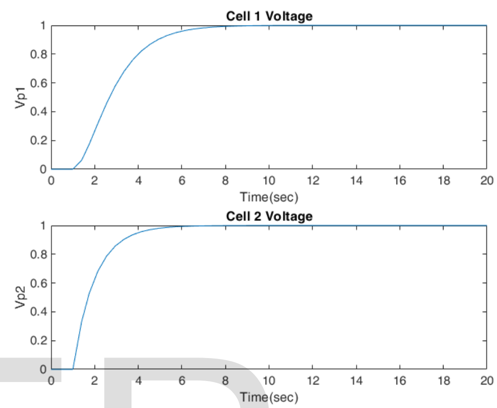


Fig. 5. Closed loop test results for the output voltage of cells 1 & 2.

Next, the same PID parameters were used but in the presence of disturbance on the output of the system. Figure X shows this response with disturbance matrix P= [0.5; 0.35], a column vector with dimensions 1x2 injected into the system at 7 seconds on the simulation clock. This disturbance was rejected as shown in the top plot of figure xx.

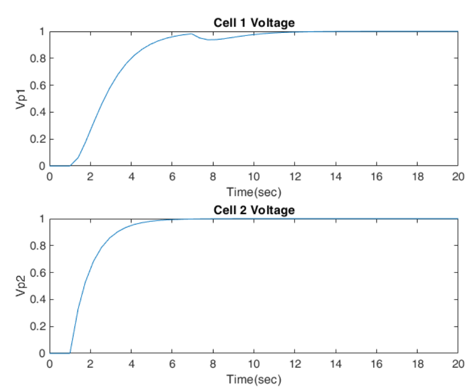


Fig. 6. Output disturbance Injection and rejection on output voltage of cell 1.

The second test for closed loop response was made on the battery ECM. This test utilized a PID controller which was tuned by the inbuilt Matlab PID tuner.

Experiment	P	I	D
Untuned	1	1	0
Tuned	1.33758	2.673552	-0.048576

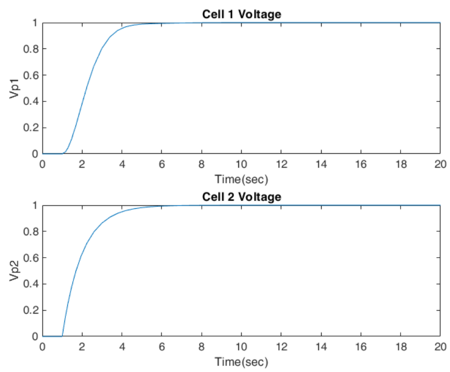


Fig. 7. Closed loop test results for the output voltage after tuning PID controller.

Figure xx shows the tuned response without disturbance injected into the output. Figure yy shows the tuned response with disturbance injected into the output.

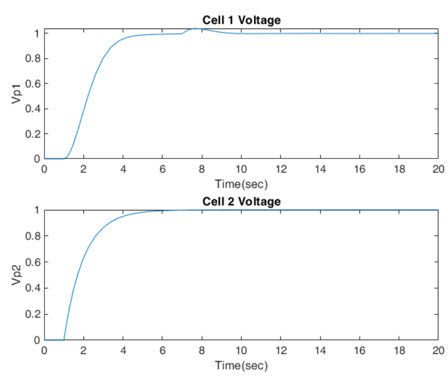


Fig. 8. Disturbance rejection after tuning PID controller for output voltage of cell 1.

5 Fuzzy Logic Control of the Battery Model

The fuzzy logic toolbox of matlab was utilized here. The call to the FLC GUI was made and subsequently the membership functions for the FLC has been designed as follows:

1. Two antecedent membership functions coming from the temperature and voltage that make up the input
2. One consequent rule forming the output which is a decision to charge (CC), no action (NA) or stop charge (SC)

With the following rule editor options assigned, the response fromo the FLC is presented next.

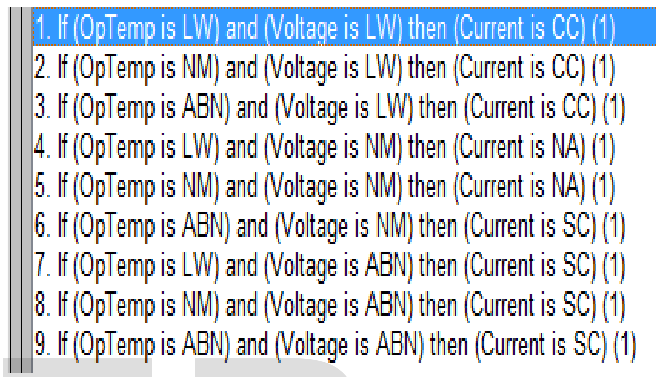


Fig. 9. FLC Rule base showing membership functions and weights.

The rule viewer is used to gain insight into the firing sequence of the assigned rules

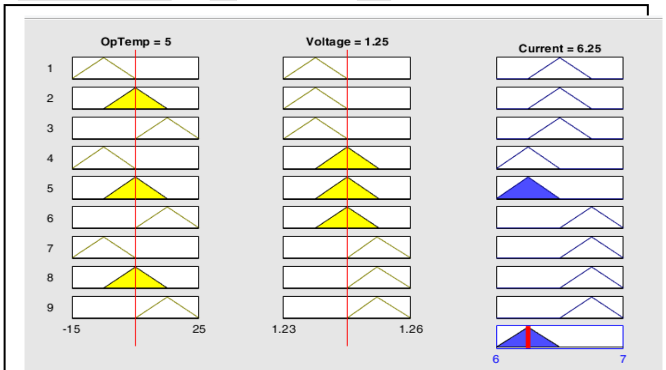
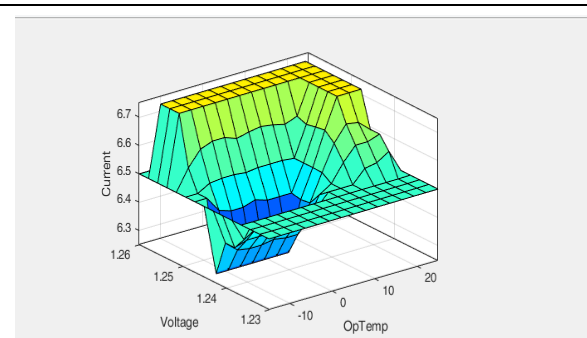


Fig. 10. Firing sequence of rules defined in Figure 9.

And the surface map of the FLC output is given as shown in figure zz



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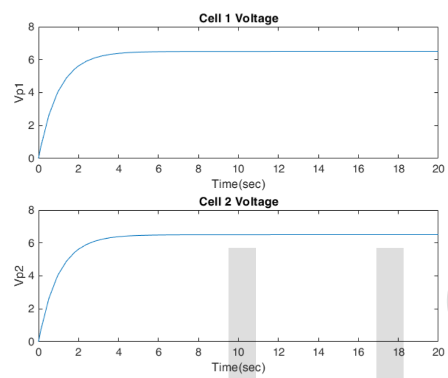

Fig. 12. FLC output for reference voltage of 6V.

The results from the PID and FLC experiments were characterized with respect to standard control system metrics such as rise time, settling time, steady state response time etc. Table 4.4 summarizes the obtained results.

Metrics	V_{p1}		V_{p2}		T_{cell}	
	PID	FLC	PID	FLC	PID	FLC
RiseTime	5.984	4.892	5.9836	4.8921	0.8221	215.5112
Settling-Time	15.92	271.6	15.9205	271.6384	3.5470e+03	783.4454
Settling-Min	1.196	3.8028e-05	1.1961	8.4752e-08	-3.8177e+09	17.9973
Settling Max	1.25	6.3597e-05	1.25	1.4174e-07	1.0801e+11	21.5724
Overshoot	0	36.03	0	36.0292	1.0330e+08	7.8990
Undershoot	0	0	0	0	3.6514e+06	0
Peak	1.25	6.3597e-05	1.25	1.4174e-07	1.0801e+11	21.5724
Peak Time	10391	268	10391	268	587	475

It can be clearly seen from the table of standard metrics that the FLC outperforms the PID controller in every metric used to control either the output voltage or the temperature of the Battery system under test.

5.1 COMPARISON EXPERIMENTS

The other results show the plots comparing the output for both the PID and FLC placed side by side.

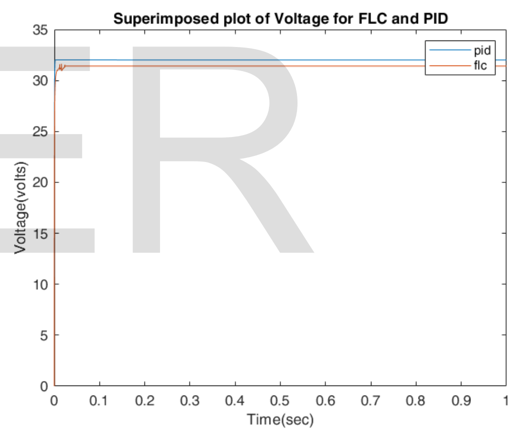

Fig. 13. Combined plot showing Voltage response from PID and FLC without disturbance injected.

Utilizing standard satellite battery voltage of 80W, 32V and 2.5A, the voltage response for the PID and FLC were plotted. Figure 13 is the response without disturbance injection.

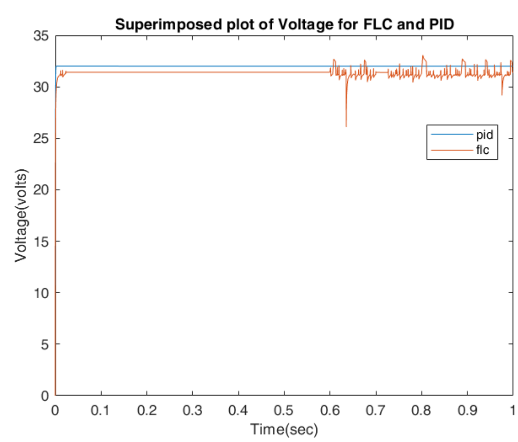

Fig. 14. Combined plot showing Voltage response from PID and

Figure 14 shows distuyrbance injected at 0.6sec.

6. COMMENTS AND RECOMMENDATIONS

Artificial intelligence (AI) techniques are becoming indispensable as alternate approaches to conventional techniques of battery power management systems. The mathematical modeling and simulation of the satellite power system were carried out using FLC. The results and interpretation shows that Fuzzy logic controllers performed better than its contemporary (PID) controller with regards to good error tracking, quick settling time, stabilization and control of the cell voltages. For future work on this work the following recommendation were made

1. That there should be a comparison of ANN (artificial Neural Network) and Fuzzy Logic system on this system.
2. Future research should be carried out on actual / physical implementation of the design using embedded system.
3. Future work should also be carried on a means of observing the control process.

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