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Thermal Battery Tester Mistakeproofing And Uncertainty Characterization

J.E. Garni, C.G. Wagner, R.A. Morgan, S.V. Crowder, and J.A. Henfling
Sandia National Laboratories
P.O. Box 5800
Albuquerque, New Mexico 87185-0613
jegarni@sandia.gov

Abstract: *Within the last 18 months, the tester team in Sandia's Power Sources Production Department has undertaken a project to improve the performance and reliability of its thermal battery acceptance testers. The project seeks to achieve two main goals: (1) to quantify an uncertainty value for tester measurements, and (2) to significantly reduce the number of costly user mistakes. Tasks identified to achieve these goals include (1) development of a software system to implement a Measurement Assurance Plan (MAP), (2) development of an automated test cable verification device, (3) enhancement of existing tester software to assist users with equipment and cable configurations, and (4) development of a highly accurate check standard to closely mimic thermal battery behavior. This paper will explain the impetuses for undertaking the project, outline and elaborate on the various tasks associated with the project, and present the project team's achievements to date.*

Keywords: check standard; mistakeproofing; uncertainty, thermal battery.

Introduction

A thermal battery is a collection of primary electrical cells with inorganic salt electrolytes and pyrotechnic materials. The electrolyte is solid at room temperature. In this state, the battery is inactive and produces no power. The battery can be activated by electrical or mechanical ignition of the pyrotechnic materials, which melts the electrolyte. Thermal batteries are one-time-use devices with a shelf life of more than 20 years. Once activated, the battery can supply electric power from a few seconds to over an hour.

In 2002, the Power Sources Production Department completed development of a Windows-based thermal battery tester to replace an aging "fleet" of testers. This tester consists of a main control computer, a Dynaload® load chassis by Transistor Devices, Inc., power supplies for battery simulation and test unit ignition, and custom-built electronics modules for routing loading and voltage sensing signals. The heart of the control computer is the Microstar Laboratories DAP5200a data acquisition board. This board can sample 16 analog-to-digital (A/D) channels, expandable to 512 channels using input expansion boards in a separate chassis. The 5200a also has two digital-to-analog (D/A) voltage output channels, expandable to 66 using a Microstar expansion chassis, and 16 digital I/O (DIO) lines, expandable to 128.

Project Motivation

At about the same time as the new thermal battery tester was placed into service, a group from Sandia's Power Sources Component Development Department was beginning development of a new thermal battery design, the first such undertaking in many years. During the initial development lot testing and first production lot acceptance testing, complaints were being voiced about "no-tests," or tests that were initiated but had to be prematurely terminated due to unexpected voltage readings or sudden voltage "drop-outs" from expected readings. Subsequent investigations revealed that, despite a very detailed set of operation instructions, tester cables were not always being properly connected or test equipment was not being properly configured. Although the tester was designed to be capable of testing a wide variety of thermal batteries, it is very often necessary to reconfigure the test equipment by routing cables between instruments and other modules. Additionally, every battery type requires that a unique set of cables and other custom-built electronic boxes be used during testing. In short, it is quite easy for test operators to make mistakes when setting up for tests.

Since thermal batteries are one-time-use devices, they cannot be recharged once activated. "No-tests" are costly in that a battery that costs thousands of dollars to produce is destroyed with no meaningful data to show for it. It became apparent that the tester needed more advanced mistake proofing capability.

As testing on the new product progressed and data sets were being scrutinized, the product engineers noticed something that made them uncomfortable: too many readings were coming dangerously close to either upper or lower pass/fail limits. This particular battery is one where the shortest, slightest voltage excursions outside of the pass/fail limits do not meet requirements. Though the tester reports a data point within the limits, could it be possible that the reading might actually fall outside the limits? How certain is it that the reported value is the actual value?

Project Vision

We envisioned an electronic battery simulator containing small, highly-accurate power supplies capable of responding to various load levels. We also envisioned using existing tester software to apply a realistic load profile to the simulator and then feed the collected data to another program that would analyze the data against previous data sets for drift trends and uncertainty. Additionally, we determined that we needed a device to attach to a train of cables used to connect a battery to the tester. This device would scan each wire in the cable to detect any discontinuity conditions.

Uncertainty Analysis

The task of designing and building the battery simulator (or "check standard" as it will be known hereinafter) went to two electronics engineers from Sandia's Geothermal Research Department. While the check standard was under development, the engineers working on it produced a small, four-channel voltage reference standard that used four references: 10-volt, 5-volt, and 3-volt references rated at 0.1% accuracy, and a 2.048-volt reference rated at 0.15% accuracy. This reference allowed us to run voltage uncertainty and drift checks on the tester until the check standard was finished.

The reference standard was then used to perform uncertainty analysis on the tester. A special program was developed to simply take input from one of the four reference standard voltage channels at the rate of 20 readings per second for 120 seconds. Twenty-five of these data sets were collected for each of the four channels. The data was then analyzed by the project team's statistician, who calculated uncertainty values for each tester voltage channel. A standard deviation value was determined for each channel; these standard deviation values were then used as the "tester uncertainty" component of the overall uncertainty calculation. A metrologist from Sandia's Primary Standards Laboratory then performed an independent analysis of the reference standard using his own test equipment and calculated another uncertainty value, known as "calibration uncertainty." Using a Root-Sum Square formula yielded a combined standard uncertainty value:

$u^2_A(V)$ = Tester Uncertainty
$u^2_B(V)$ = Calibration Uncertainty

$$u_c(V) = \sqrt{u_A^2(V) + u_B^2(V)}$$

$$= \sqrt{(0.014V)^2 + (0.000171V)^2}$$

$$= 0.014\,V$$

Since the number of samples in the two analyses was different, the Welch-Satterthwaite Formula was used to calculate effective degrees of freedom:

$$\nu_{eff} = \frac{u_c^4(V)}{\dfrac{u_A(V)^4}{\nu_A} + \dfrac{u_B(V)^4}{\nu_B}} = \frac{(0.014)^4}{\left(\dfrac{(0.014)^4}{25} + \dfrac{(0.000171)^4}{17}\right)}$$

$$\cong 25$$

The expanded uncertainty was then calculated using the coverage factor determined from the t-distribution for a 99.73% level of confidence [1]:

$$U_V^{99.73} = t_{99.73}(25)\, u_c(V)$$

$$= (3.33) \times (0.014) V$$

$$= 0.047 V$$

The uncertainty value for the first voltage channel is ±0.047 volts. Table 1 shows the uncertainty values for the other reference standard channels, calculated in the same manner.

TABLE 1. Tester Uncertainty Values Using the Voltage Reference Standard

Channel	Avg (V)	Std Dev (V)	Total Uncertainty (V)
1	10.03	0.014	± 0.047
2	5.01	0.011	± 0.037
3	3.02	0.0072	± 0.024
4	2.06	0.0053	± 0.018

It should be noted that the tester gathered data on channel 1 through a 4-to-1 voltage divider, while the other channels used 3-to-1, 2-to-1, and 2-to-1 dividers, respectively. This might explain the higher uncertainty numbers for channels 1 and 2 as opposed to those of channels 3 and 4, since any scatter in the data is magnified more dramatically for a greater voltage divider value. Voltage dividers are used in the tester because typical thermal battery outputs range well above the 10-volt limit of the Microstar A/D board used by the tester.

During the design phase of the tester in 2002, it was determined that it would feature an "on-the-fly" data filtering algorithm to help reduce the size of data sets to a manageable level. Later, the tester software was modified to allow for the specification of time intervals where this filtering feature could be defeated, allowing for capture and storage of all 1000 data points per second. Analysis of these unfiltered data sets revealed a data stream that exhibited characteristics of a 60Hz AC sine wave. A thorough investigation of the tester determined that noise was being induced by AC-powered isolating transmitters used to condition voltage signals going to the A/D board. The team's statistician performed an analysis of the data and determined that about 75% of the variation in the data was caused by the AC-induced sine wave. He also projected that uncertainty values could be improved by anywhere from 65% to 90% if the AC noise could be eliminated from data signals. The team is still working to correct this.

Tester Drift Detection

The four-channel reference standard was also used to test the measurement assurance plan (MAP) software developed by one of the team's software engineers. This software allows a user to specify different test parameters (single readings, average readings, maximum readings, minimum readings, or standard deviations) to capture at various times or time intervals during a test. Captured information is then stored in a database so that it can be compared against similar data from previous tests in order to determine whether the tester's data acquisition hardware is drifting. For example, a user may want to capture the voltage on channel 1 at 1.0 seconds, or may want to know the average reading on channel 3 between 1.0 and 2.0 seconds of elapsed test time. Control limits must be specified for each test parameter.

The voltage reference standard (and eventually the check standard) is connected to the tester and operated in the same manner as a battery. At the end of the test, the MAP software gathers information for each specified parameter, stores the results in a database, gathers historical information for each specified parameter from the database, and presents graphs of each parameter with the most recent and historical data as well as the control limits. Figure 1 shows an example of a historical analysis of voltage data taken on the reference standard's 10-volt output at one second of elapsed test time.

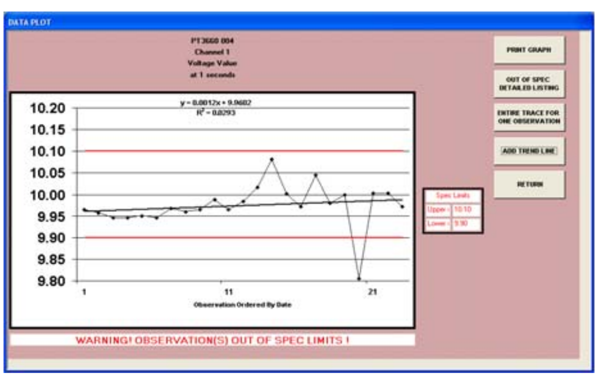

Figure 1. MAP Software Drift Detection Example

Upon inspection of each graph, the user has the option of displaying a trend line through each graph in order to assist with analysis of data drift. Our goal is that the tester's ability to accurately detect drift will determine a reasonable time interval between tester calibrations. Right now, the four thermal battery destructive testers (two at an out-of-state facility) are calibrated every three months, requiring a significant expenditure of money and man-hours. The MAP study will allow us to widen that time interval.

The Cable Tester

The Cable Tester is now in its prototype phase. It is a small handheld device used to calculate the resistance of a cable or sequence of cables used in the thermal battery tester operation. The primary purpose is to ensure that all cables are connected in the proper sequence. It also provides a record of the resistance of the cable(s) to ensure long term stability.

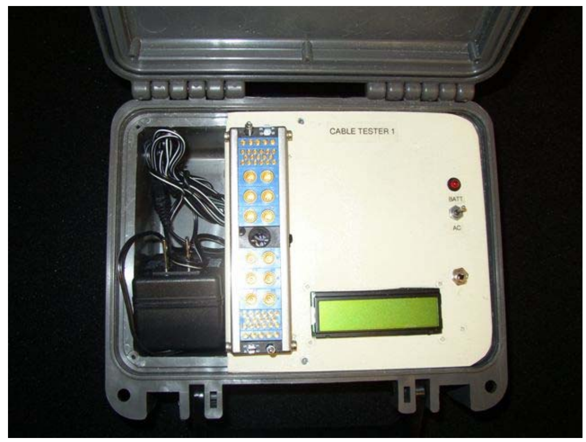

Figure 2. Cable Tester

The Cable Tester is both an AC and battery powered device using the Parallax Basic Stamp Microcontroller and the Micromega uM-FPU Co-processor chips. It uses a Powertip BPK216 LCD display. A connector is placed on the 'battery' end of the cable and used to connect or 'loop back' pairs of signals. A set of four uM-FPU processors are used to measure 4 sets of signals, LD1+ & LD1-, Sense1+ & Sense 1- for each battery tap to which the cable connects.

The Basic Stamp controls the top level operation, addresses the display, and instructs the co-processor to perform required operations. There are two channels of input on the co-processor, each of which a known, 1% resistance, and the connections to the cable under test are attached in a voltage divider string. Since the resistance of a good cable will be small, typically less than 1.5 Ohms, a current can be calculated using the value of the known resistor. The co-processor then reads the voltage value across a pair of wires from the cable under test (LD1+, LD1-). This value is divided by the known current to achieve a highly accurate value of resistance for that pair of cable wires. This value is then displayed and held for a few seconds on the LCD display. The voltage of another pair of wires is then read and the resistance determined.

Cabling and Configuration Diagrams

Another useful mistakeproofing tool is the set of tester cabling and configuration diagrams that has been added to the tester software. These diagrams show the routing of cables between tester electronics chassis modules and also between the tester and the battery. They also point out where specialized electronics modules need to be inserted in the tester circuitry should a battery require them.

The configuration diagrams work in conjunction with the existing pre-test check software. A power supply within the tester equipment rack is used to simulate a battery at the battery's nominal voltage and heaviest load, and the tester reads back the power supply outputs. If the readings are outside the tolerance band, there is probably something not connected properly. It is at this point that the user will be able to request a display of configuration diagrams. These visual aids will be of great benefit toward accomplishing the goal of reducing the number of "no-tests" in the future.

The Check Standard

As of the writing of this paper, a check standard prototype is nearing completion. The standard will be connected to the tester and will wait for an activation signal (the same signal that ignites a battery) to begin its activity. It will simulate the voltage rises that thermal battery taps experience within a fraction of a second after ignition. It will output voltage data to the tester and its internal power supplies will draw current based on a loading profile specified by the tester. Additionally, it will collect its own set of voltage and current data at a higher rate than the tester. Eventually, a software program will be developed to compare the tester data set against the standard's data set for agreement.

The standard is comprised of four programmable power supplies to simulate four battery taps. Each power supply is rated at 23 volts maximum with a 10-amp current limit. There are eight analog-to-digital (A/D) conversion modules for capturing voltage and current output data, and signals pass through signal conditioning and filtering circuitry before they reach the A/Ds. Four digital-to-analog (D/A) converters handle programming of the output voltage ramp-ups that simulate a thermal battery's voltage rise immediately after activation. The standard uses dual microprocessors, one to ramp output voltages from zero to nominal when the activation signal is received from the tester, and the other to collect data and store it to a file on the on-board USB flash drive. The standard is powered by a 28-volt lithium-ion power pack similar to those used by cordless power tools.

The first version of the prototype was connected to the tester and collected excellent data from the four voltage outputs. In fact, during quiescent time intervals where no load was being applied, check standard voltage channels showed no more than 6mV of scatter. The standard was also able to successfully detect the battery activation signal to synchronize its data collection activity with that of the tester. Voltage rise simulation data also looked as expected. The second version will feature better on-board data acquisition and load response.

Figure 3. Check Standard Prototype

Summary

To date, the project team has made great progress toward realizing the original project vision. Uncertainty analysis has been performed on the tester, the cable tester and check standard development is progressing nicely, and the MAP and configuration diagram software is mostly complete. While there is still check standard verification, cable tester verification, prove-in, and documentation to complete, once these steps are completed the tester will be equipped with a powerful set of tools that will greatly elevate our customers' confidence in its performance.

Acknowledgement

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References

1. ISO, International Standardization Organization, *Guide to the Expression of Uncertainty in Measurement* (1993).