WHITE PAPER

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Developing an advanced, predictive battery health monitoring solution with a low-cost microcontroller solution

Introduction

In today's world of advanced communication, industrial process control and automotive systems, the reliance on batteries to ensure power delivery is always available is becoming increasingly critical. Because of this, the ability to monitor the battery life-span and predict failure points is also becoming ever more important, but this is completely addressable with off the shelf microprocessor technology and software. In this paper, we will explore two different types of failure and lifespan prediction in battery systems: 1) Electrochemical Impedance Spectroscopy (EIS) and 2) Resistive measurements. Although both technologies can be implemented on their own to measure battery health, combining the two in a simple fashion on a low-cost microcontroller platform further increases the usefulness of the information collected.

With many applications – automotive start-stop systems, advanced uninterruptable power supplies (UPS) for server and telecom applications and even hybrid automotive designs – predicting the failure point, available capacity or lifespan of battery back-up and power delivery systems is becoming more challenging for power electronics system designers. Especially in the case of UPS and telecom systems, the cost associated with the deliberate disconnection from AC mains, in conjunction with the long recharge cycle times that some of these batteries can have, drives the need for a more non-invasive fault prediction and monitoring solution. By taking advantage of the higher processing performance, system integration and communications peripherals of modern microcontrollers, one can develop a low cost, robust solution to fulfill this need based on EIS. This method, while completely non-invasive to the battery, offers a distinctly different perspective on the health and capacity of a battery system above and beyond simple current and voltage measurements. Although it is said that neither can match the absolute testing results of pure load testing, both are proving to be a low cost, reliable and time-effective solution or replacement.

Battery basics

Before we look at the different techniques of battery testing, let us first examine how a battery "looks" internally while under test. For simplicity in this paper, we will use the standard lead acid battery as our model, although load testing and EIS testing will work on other battery technologies. Per the Randles battery model (Figure 1), the battery is seen as a set of electrical components consisting of resistors and a capacitor. A battery model contains purely ohmic resistance, as well as capacitive and inductive reactance. Impedance, in respect to EIS, refers to all three values.

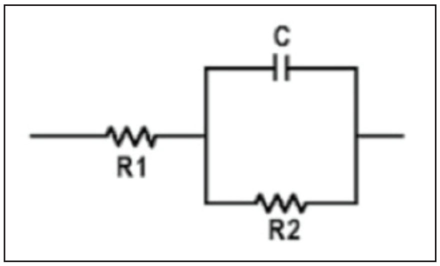

Figure 1: Simplified Randles Model of a common lead acid battery.

Load testing

Let us examine traditional methods of testing a battery system. The most basic and reliable test to measure the ability of a battery to perform to its rated capacity is the tried and true "load test," in which a cell or string of cells is subjected to a load current that matches the normal operating discharge that the system may encounter under normal conditions. For example, load testing the UPS of a telecom base station would involve disconnecting the station itself from AC mains, hooking up a secondary power supply and running the system on battery backup until the point of power failure from the battery pack. While very cost prohibitive in terms of labor (hooking up additional power supplies, disconnecting AC mains), this method is also prohibitive in terms of system up-time. In this example, the system will need to continuously run on battery back-up power until the battery unit is completely discharged and then go through an entire recharge state, which may take in excess of 36 to 48 hours. While the system is being recharged, it will still need the additional test setup battery bank connected in terms of a disconnection from the AC mains during the recharge period. This would mean a technician would need to be on site for multiple days, including multiple days of connection and disconnection of a secondary battery system to perform the testing. While a load test does perform a near 100 percent system integrity check and will identify any pre-existing problems in the battery cells or conductive paths, this is rather time consuming – and costly.

There is a second option for load testing of battery cells that does not include a complete working-level discharge of the battery bank. This includes introducing a short duration load of varying load ranges (based on the rating of the battery itself.) By measuring the voltage drop divided by the sunk current, this will give us the resistive value of the battery itself and is considered to be very accurate and repeatable but does have the potential to harm the battery due to potentially excessive heating.

Resistance testing

Resistance testing, while similar to load testing is not a new battery management technique, it is quickly becoming commonplace for failure prediction, as well as proving to be a cost effective and reliable indication of battery cell health.

Because the internal resistance of a battery can be closely correlated to its capacity, it is thought that this technique alone can be used as predictive measurement of the battery pack performance during discharge. Based on field testing by multiple battery and battery test-equipment manufacturers, it has been shown that if a battery has had a change of greater than 25 percent above its known good value, this battery will most likely fail a load test condition. EIS testing is a derivative of resistance battery testing, and by utilizing the high speed Fast Fourier Transform (FFT) processing of microcontrollers can be now be implemented at the application level.

Electrochemical Impedance Spectroscopy (EIS)

As previously mentioned, EIS testing is a form of resistive testing for battery systems. Unlike load testing, which requires the battery under test to be temporarily disconnected from the application, EIS can be done on-the-fly, even while the application is under load. Also, unlike load testing, whether its complete deep cycle discharging or short-burst testing, EIS completely non-invasive to the battery under test and also offers the advantage of being able to be averaged over time to improve the signal to noise ratio. With an in-application microcontroller solution, data points can be taken in real-time or over longer durations and averaged together, as the battery impedance does not change instantaneously. This is also advantageous in applications where the battery is being subjected to normal use. For example, in an automotive start-stop system where the vehicle is running on engine power, the processor can be checking the battery in the background and communicating with the vehicle host controller to a.) Warn the driver that the battery may be failing and b.) Disengage the start-stop system so the driver does not encounter a stall at the next stop-light. In a UPS system, EIS can be used on a daily or weekly interval to check the health of batteries and warn the system operator if there is a potentially failing battery cell or string of cells.

When implementing EIS, we are essentially creating a frequency analyzer that is designed to generate a low-level AC signal which is driven into the battery, and we then measure the corresponding voltage response. This signal can range in frequency from a few µHz up to the kHz range and is usually in the 10mV per cell range as to not cause any heating within the battery. A DC current can also be introduced to the corresponding AC signal in order to set a baseline for the device under test but is not necessary. In accordance with Ohms Law, a simplified expression can be given below (Figure 2) with the system impedance expressed in terms of phase shift ϕ, and magnitude, Z_0.

$$Z = \frac{E_t}{I_t} = \frac{E_0 \sin(\omega t)}{I_0 \sin(\omega t + \phi)} = Z_0 \frac{\sin(\omega t)}{\sin(\omega t + \phi)}$$

Figure 2: Impedance calculation with Ohm's Law

By utilizing the basics of Ohm's Law and adding additional FFT calculations for additional resolution over multiple period and frequency domains, we can very accurately calculate the complex impedance of our battery system.

In a microcontroller-based, active excitation (using the outputs of the controller to generate the AC signal, rather than relying on system loading), our block diagram would look similar to Figure 3, when using a Texas Instruments C2000™ microcontroller. Z1, Z2 and Z3 represent the different mixed complex networks comprising the battery's equivalent circuit.

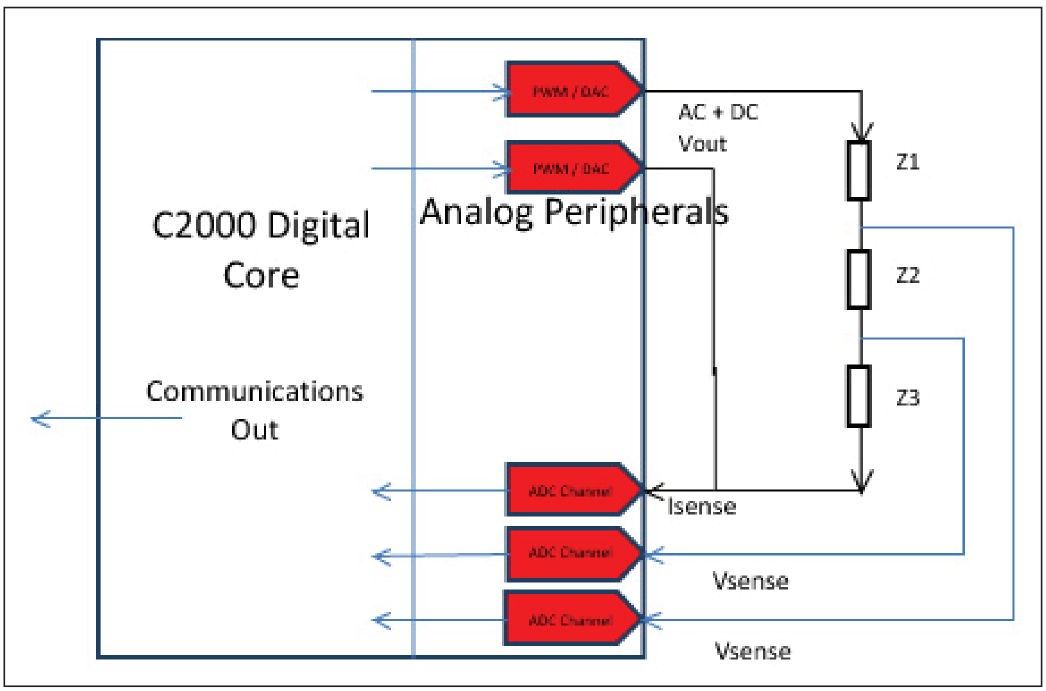

Figure 3: A microcontroller-based, active excitation block diagram using a Texas Instruments C2000™ microcontroller.

As you can see, with the C2000 device, we are able to generate the active AC signal (and DC signal, if implemented as a baseline) by utilizing the high-resolution pulse-width modulation (PWM) generators. Operating as a digital-to-analog converter (DAC), the PWM generators have the ability to generate a DC or AC output with greater than 16-bit resolution, up to frequencies in the 100kHz range, with an output voltage that is scalable up to 3.3V. With integrated 12-bit analog-to digital converter (ADC) inputs, we can now measure the return voltage and current sense to complete the measurement circuit. This enables us to have a complete, closed loop measurement system with minimal external components and the ability to provide even more functionality to the design.

The C2000™ microcontroller advantage

Based on the highly adaptable TMS320C28X digital signal processor (DSP) core, the C2000 microcontrollers offer a high-performance, scalable processor solution to not only EIS on a battery system, but the capability to control the aspects of an associated power stage connected to the battery systems, as well. Featuring a native 32-bit processor with both fixed- and floating-point options, as well as hardware accelerators for FFT calculations, there are multiple options available to engineers to develop systems ranging from just the battery management functions all the way up to complete, digitally controlled power stages.

Important C2000 features include:

- Prices starting under $1.50
- Code-compatible scaling from 40MIPS to 300MIPS
- Fixed- and floating-point math capabilities
- Secondary Control Law Accelerator (CLA) core for advanced control loop flexibility
- FFT and Viterbi Complex Math Accelerators (VCU)
- Integrated FLASH and SRAM Memory
- Up to 19 PWM channels, including up to 8 PWM channels with up to 55ps resolution
- Up to 3 on-chip analog comparators
- 12-bit ADC with 16 channels and a maximum sampling frequency of 4.6 Mega-samples per second
- CAN, LIN, I2C, SPI, UART and USB connectivity options
- Operating temperatures up to 125*C with AEC-Q100 Automotive Certification
- Devices with ARM Cortex-M3 cores for additional connectivity and system control

The C2000 family of microcontrollers is supported by a wide range of development kits, starting at $17 and include applications such as LED lighting, digital power supplies, advanced motor control systems and more. In conjunction with the development kits, an array of library functions including specific processing algorithms such as FFT functions, PWM and ADC drivers. Reference documentation for all of the C2000 hardware and software is available for free in the controlSUITE™ software environment, available for download at www.ti.com/controlsuite.

Beyond battery management

With the density of peripherals available, combined with the processing power of the C2000 microcontrollers, it is possible to combine functions multiple functions of the end application into a single processor. As an example, we will look at the implementation of EIS, voltage, current and switching power stage in an electric vehicle application, all controlled with a single, automotive qualified microcontroller. Figure 4 below shows a simplified configuration utilizing a single C2000 microcontroller to control both the power stage, as well as handling the EIS measurement stage.

As you can see in this diagram, we have implemented the same measurement loops as in the standalone ESI block diagram from earlier, as well as added the functionality of digitally controlling a buck/boost power stage. Two of the PWM channels of the device are used to drive the AC and DC voltage source for the EIS measurement. Four additional PWM channels are then used to drive the four switches of a synchronous buck/boost power-supply stage. A single ADC channel is required to close the control loop for the power supply stage within the system. For customers looking for additional horsepower when running FFT functions, C2000 devices offer the VCU as an additional accelerator, as shown on the diagram. This can be used to offload FFT calculations from the main processor, allowing even more background tasks to be handled in the device.

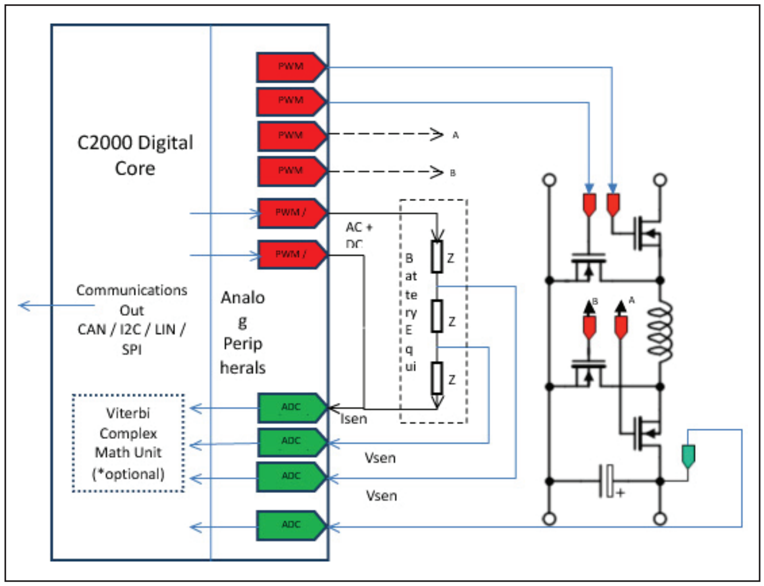

Figure 4: Simplified system configuration utilizing a single C2000 microcontroller to control both the power stage, as well as handling the EIS measurement stage.

Although not shown on the diagram, with the integrated analog comparator functions of the C2000 devices, we can also add the protection of an over-voltage or over-current disconnect function, still using a single microcontroller approach. Also, there are still additional ADC and PWM channels available on the microcontroller. This would allow a designer to add even more functions, such as the more standard battery measurement functions like current and voltage measuring.

Although the primary application focus of this paper has been on hybrid automotive systems, the range of uses for EIS continues to grow. As previously mentioned, it is gaining more and more recognition in the UPS and telecom market space, where providers require as close to a 100 percent up-time as possible and where battery testing has become expensive. Other potential areas of use have also been explored. EIS is not just a technology that can be used for battery monitoring, it can also be used in applications such as fuel cells or other applications in which there is a dielectric interface.

For Further Reading

"Using PWM Output as a Digital-to-Analog Converter on a TMS320F280x (Rev. A)"
http://www.ti.com/lit/spraa88

"Bringing efficient communications to real-time motor control and power conversion applications with TI's Viterbi Complex Math Unit (VCU)
http://www.ti.com/lit/spry158

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