Preliminary Design of a Smart Battery Controller for SLI Batteries

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Abstract

Automotive start, light, ignition (SLI) lead acid batteries are prone to capacity loss due to low temperatures, self-discharge, sulfation and shorting of plates. Monitoring and charge control of these batteries can be improved by using the concept of a smart battery system (SBS). In a SBS, battery data from sensors embedded in the battery package are acquired by a smart battery controller which processes this data, and transmits charge control information, to a central processor for effecting control actions.

Since 1997, Villanova University and US Nanocorp, Inc. have collaborated on the development of a patented fuzzy logic-based method for determining the state-of-charge/ state-of-health (SOC/SOH) of a battery.

In the present project, a smart battery controller is being developed which is optimized for using the fuzzy logic methodology for determining the SOC/SOH of an automotive SLI lead acid battery. The present paper reports on the preliminary design and testing of this fuzzy logic-based smart battery controller.

Introduction

Automotive start, light ignition (SLI) lead acid batteries are the most widely used batteries in the world. Lead acid SLI batteries are designed to provide short bursts of high current on a regular basis. In an automobile, the batteries are crudely recharged by an alternator with very limited charge control. Lead acid batteries also have a relatively high self-discharge rate and suffer significant capacity loss with reduction in temperature. In the application to tanks and armored personnel carriers, these are big concerns since these vehicles are dormant for several months and the SLI lead acid batteries must be able to start the vehicle following this dormant period even under cold weather conditions. If the SLI lead acid batteries remains in a low state-of-charge (SOC) for extended periods of time, the electrolyte may stratify into vertical layers (according to the density of the electrolyte). This may result in *sulfation*, the growth of large crystals on the plate, which reduces battery capacity and shortens battery life. The growth of dendrites which can short out neighboring plates is also promoted by stratification of the electrolyte resulting from the lead acid battery remaining in a low SOC for an extended period of time. If more than one SLI battery are in a series string, e.g. in a 36 V system, it may also be necessary to perform a periodic equalization charge. It is clear that to optimize the reliability and life of an automotive SLI battery, careful charge and discharge control are required.

Smart batteries offer a paradigm shift in battery management and control. A sensor attached to the battery continuously conveys information regarding the battery's condition to a central controller over a smart battery bus. The controller then activates a battery charger with a dynamic charge control to optimally charge a deficient battery, limits the discharge of batteries to prevent their over-discharge, and activates alarms/warning lights to indicate the impending low SOC of a battery.

The SOC of a battery may be estimated using various combinations of interrogation and data analysis techniques. Recently, researchers at Villanova University and US Nanocorp have collaborated on using fuzzy logic-based methods, combined with either Coulomb counting or electrochemical impedance spectroscopy (EIS) to determine a battery's SOC and SOH [1-4].

In the present project, the goal is to develop a fuzzy logic-based smart battery controller for automotive SLI batteries. In this paper we report on the preliminary hardware/software design of this fuzzy-logic-based smart battery controller.

Smart Battery System

A smart battery system (Fig. 1) comprises a host device (controller), a smart battery, a smart battery charger, a system management bus (SMBus), an AC/DC converter, and a system power supply [5]. As can be seen from Fig. 1, many features are available to the smart battery controller designer including accurate battery SOC/SOH information,

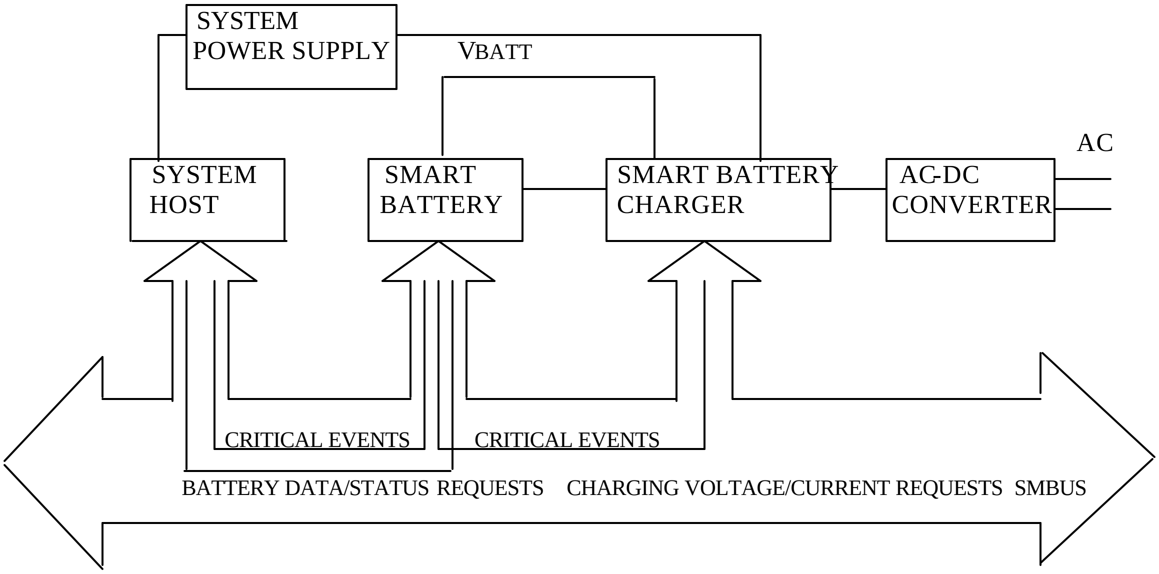

Figure 1 Block Diagram of a Smart Battery System

remaining time required to fully charge the battery, storing of performance data, and charging profiles tailored to particular battery chemistries. While this extensive list of features is useful in other smart battery applications, e.g. laptop computers, only a limited subset is useful for an automotive SLI lead acid battery. The key features required in this type of smart battery system include much better charge control than is presently offered, a battery SOC/SOH indicator, storage and means of retrieving battery usage history, a means of preventing over-discharge of batteries, and equalization charging if two or more SLI batteries are used in a series string.

Existing Smart Battery Controllers

Two representative smart battery controllers widely used in portable electronic products are the Texas Instruments bq2060 [6] and the Power Smart PS 331 [7]. Both controllers offer high resolution 14/15-bit analog-to-digital (A/D) converters to convert the sensed analog battery current, voltage, and temperature into a digital signal for processing, support the 2-wire SMBus v. 1.1 interface, are low power consumption devices, and are available in 28-pin surface mount SSOP packages. The bq2060 and the PS331 chips both provide 4-5 LED segment display outputs for displaying the battery SOC. Both controllers are interfaced to an external EEPROM which store the battery models, battery configuration data, self-discharge data, etc. for various battery chemistries.

The primary advantage of developing a fuzzy logic-based SOC model approach over conventional approaches is the code efficiency of the models. This means that the battery chemistry models may be stored in on-chip programmable, FLASH memory instead of in external EEPROM, since the fuzzy models would typically only occupy ~ a few hundred bytes of memory. Additionally, the fuzzy logic method allows fast model development time for new battery chemistries/geometries since we have observed that small data sets can be used to develop models of good accuracy [4].

Preliminary Design of Fuzzy Logic-Based Smart Battery Controller

Controller Architecture

The preliminary design of the fuzzy logic-based smart battery controller uses an 8-bit architecture. All the data are 8-bit words and the data bus is 8-bits wide. It contains a controller, a decoder, a register file, arithmetic logic unit (ALU), two index registers, several special registers, a program counter (PC) block, the Fuzzy Logic block, a serial communications interface, and program and data memory. A block diagram of the smart battery controller is shown in Fig. 2. The various functional blocks of the CPU are as follows:

Controller: decodes the instructions and gives out control signals to other parts.
Register File: contains 32 8-bit general use registers.
ALU: performs the calculations
Register X and Y: index registers.
Register A, B: accumulators.

Program Memory: stores the program code.
Data memory: stores working data.
Address Bus: 12 bit, 4K byte addressing space.
Fuzzy Block: performs the fuzzy logic calculations
Instruction Set: 26 basic microcontroller instructions and 4 fuzzy logic instructions

The address architecture of this smart battery controller is a three-address structure that is commonly used in modern reduced instruction set computer (RISC) processors. It completes the operation

$$C= A+B$$

(and most other operations) in one cycle. To do this requires a three-ported register file that can independently read two operands and write a third. There are a total of 32 registers in the register file. The first register r0 is a special one. All the operations on this register are no operations (NOPs) which provide a convenient way to implement some move operations very easily.

The PC block gives out the PC value to the program memory. The address bus is 12 bits wide, with a total of 4kB of addressable memory space. On reset or power up, the PC resets to "0x000" at the next clock rising edge. Incrementing of the PC is controlled by a state machine. The PC block also has an input that stores the branch PC value. In the instruction set, there are several control or transfer instructions. When running these instructions, there are new PC values which provide the addresses of subsequent instructions.

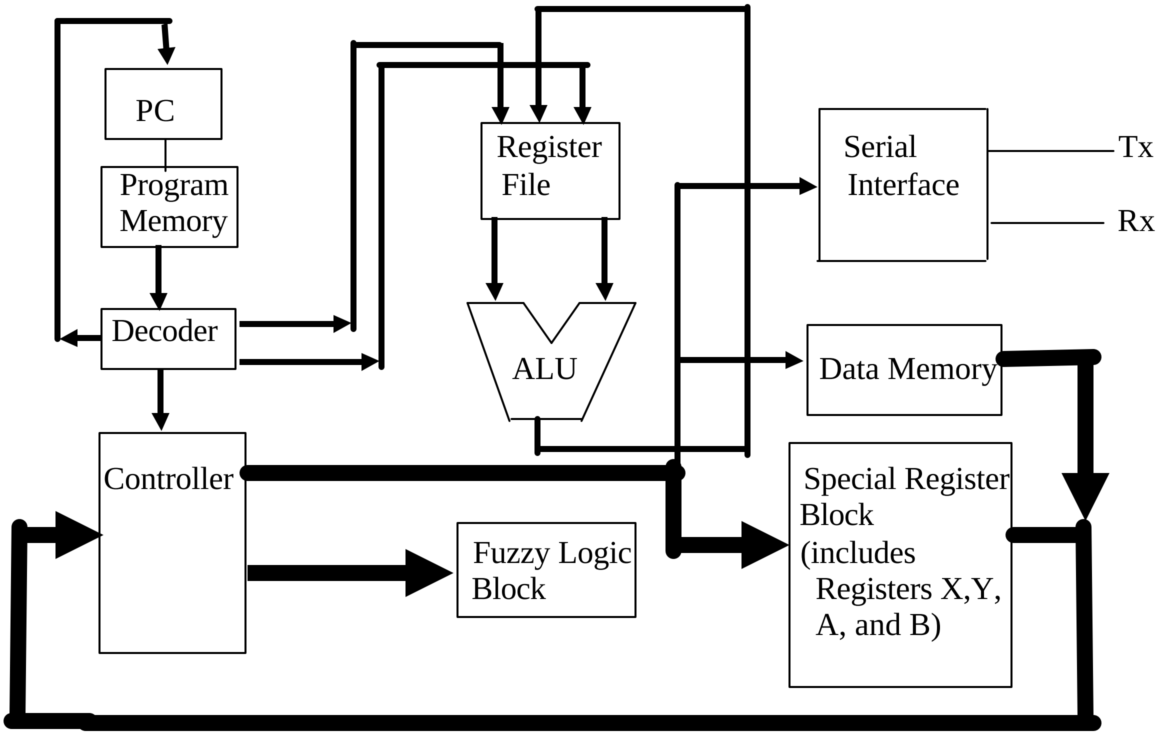

Figure 2 Architecture of the Fuzzy Logic-Based Smart Battery Controller

The Controller is the main process unit. It has a state machine that controls the operation of all instructions. It gives out all the control signals to all other blocks. It decodes the instructions in detail. Because our smart battery controller is not a RISC design, the instructions do not have the same length. It is therefore necessary to use a state machine to control processor operations, i.e. fetching, decoding, executing, memory accessing, and writing back.

In RISC processors, the instructions are pipelined, i.e. in every clock cycle, one new instruction is fetched and one instruction is finished. To do pipelining, every step should be finished in one clock cycle. Our design is a CISC (Complex Instruction Set Computer) computer in which there is no pipelining of instructions. This was found necessary to implement the fuzzy logic instructions. Some fuzzy logic instructions require more clock cycles than some of the basic microcontroller instructions. Sometimes, the number of cycles in performing fuzzy logic instructions is variable depending on the number of fuzzy rules or fuzzy membership functions. Thus in our smart battery controller design, a state machine is used, because it is a better way to manage different types of instructions.

Fuzzy Logic Instructions

The Fuzzy Logic Block is a block which completes the fuzzy logic related instructions. These include FUZZIFY, INFER, DEFUZZIFY and DIVIDE functional blocks. The first step in fuzzy logic model development is the fuzzification of the input data. The FUZZIFY instruction is used to perform the fuzzification process. During fuzzification, acquired input values (e.g. battery current) are compared against stored input membership functions to determine the degree to which each fuzzy set label (e.g. “HIGH”) is true. This is done for each fuzzy set label. The FUZZIFY instruction performs this calculation for each fuzzy set label for one input. To perform the complete fuzzification task for a system, several FUZZIFY instructions must be executed, for each of the input variables, usually in a program loop structure.

The INFER instruction is used to perform rule evaluation in the fuzzy logic model. This step processes a list of rules from the knowledge base (stored in external EPROM) using current fuzzy input values from RAM memory, and produces a list of fuzzy outputs which are also stored in RAM memory.

This final step in the fuzzy logic program combines the raw fuzzy outputs into a composite fuzzy system output. Unlike the trapezoid shapes used for inputs, in our design, we use singletons for output membership functions.

The DEFUZZIFY instruction calculates the numerator and denominator sums for weighted average of the fuzzy outputs according to the formula [8]:

$$SystemOutput = \frac{\sum_{i=1}^{n} S_i A_i F_i}{\sum_{i=1}^{n} A_i F_i}$$

where n is the number of fuzzy set labels of a system output, Si are the singleton positions from the knowledge base, Ai are the areas of the output membership functions, and Fi are the fuzzy outputs from RAM memory. The final divide is performed with a separate DIVIDE instruction placed immediately after the DEFUZZIFY instruction.

Design Implementation and Testing

The digital hardware design of the fuzzy logic-based smart battery controller described above was developed in software using very hardware description language (VHDL). The VHDL code was compiled using VCOM (from ModelTech [9]) and a functional simulation of the design was performed using VSIM (also from Model Tech). Having checked the corrected functional behavior of the design, a Mentor Graphics tool, Leonardo, was used to perform the gate-level synthesis of the design. The target hardware technology for the synthesis was an ORCA field programmable gate array (FPGA) board [10]. This testbed allows hardware design verification, at the gate level, prior to laying out an application specific integrated circuit (ASIC) chip. The particular ORCA FPGA board used for testing our design was the OR2C40A which provides a capacity of about 3,600 flip flops or up to 40,000 gates.

The design was synthesized in Leonardo (targeted to the OR2C40A FPGA board) and then downloaded onto the board for testing. Some of the basic microcontroller instructions, all of the fuzzy logic instructions, and the transmit instruction for the serial peripheral interface were all tested and found to generate correct and accurate functionality. The next step is to now lay out the present design at the transistor level and simulate this prior to fabricating the device.

Conclusions and Next Steps

The gate level design and verification of a smart battery controller for an automotive SLI lead acid battery, which is specifically optimized to employ fuzzy logic methods for battery SOC and SOH determination, has been successfully accomplished. The next step is to take the gate level design and lay it out at the transistor level. This is currently in process with a 1.5 μm CMOS technology targeted for the transistor-level implementation. The ASIC design will be simulated and verified prior to sending it out for fabrication.

An 8-bit A/D converter has also been designed targeting the same 1.5 μm CMOS technology and will also be fabricated. Assuming both the smart battery controller IC and the A/D converter work as expected, the two devices will be integrated into a single design.

It is important to note that while the PowerSmart and Texas Instruments smart battery controller chips use 14-bit A/D converters, because of the large dynamic current range that must be monitored in laptop computers for accurate Coulomb counting (and hence battery SOC prediction), this is not necessarily the case in a vehicle. Two levels of currents need to be considered. The first is the starting current of the vehicle which will be several hundred amps and the second is the current being drawn from the battery when it is powering auxiliary equipment in the vehicle. Our present design concept is to have two separate current measurement circuits. The first one employs a Hall effect sensor to monitor the high current drain and is brought into the circuit only when the starter motor is being turned over (this can be interlocked with the ignition switch). The second is a low level current monitor, based on a sense resistor, which can accumulate the auxiliary current draw over time. Using this approach, the dynamic range of current variation will not be expected to vary over several orders of magnitude (as in laptop computers) during normal operation of the vehicle. As a result, we anticipate that an 8-bit A/D converter will provide sufficient accuracy for the present project. However, this may be modified as the project progresses.

The present serial communications device incorporated into our smart battery controller is a simple serial peripheral interface that is not targeted at any particular communication standard. The communications standards developed for smart battery controllers presently used in portable electronic products are built around either a one-wire (HDQ16) or two-wire (SMBus v. 1.1) interface. However, vehicles themselves have local area networks of distributed sensors based on different standards, e.g. SAE J1939 standard. Once a final standard has been selected for the automotive smart battery, a suitable communications interface for the smart battery controller will have to be designed.

There are many other issues that still need to be considered, including cost and power consumption of the chip. The clock frequency of the chip needs to be selected to optimize these factors (in the preliminary chip design, the clock frequency being used is 25MHz; however, this is far higher than necessary for this type of application). The specific functions that the smart battery controller must provide still need to be developed. Also, on-chip power management, e.g. sleep mode, incorporated into the chip design, to minimize power consumption of the chip, must be added. Finally, the packaging of the smart battery with the automotive lead acid battery needs to be designed.

Nevertheless, a good start has been made to developing an automotive smart battery controller based on fuzzy logic and we look forward to updating the battery community on the development of this device in future workshops.

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References

1. P. Singh and C. Fennie, Jr., “A Method for Determining Battery State of Charge Using Intelligent Systems,” *U.S. Patent No. 6,011,379,* Jan 4, 2000.

2. Craig J. Fennie, David E. Reisner and Pritpal Singh, ”Fuzzy Logic Determination of Battery State of Charge – A Powerful tool for Battery management,” in *Electric and Hybrid Vehicle Technology 1999* (UK & Technology Press, Dorking, UK, 1999), pp. 116-122.

3. S. Arey, V.R. Gaddam, Z. Yang, P. Singh, C. Fennie, and D.E. Reisner," Fuzzy Logic enabled SOC monitoring Meters for NiMH Batteries," *Procs. EVS-16,* Oct 14-16, 1999, Beijing, PR China.
4. P.Singh, C.Fennie and D.E.Reisner, "Fuzzy Logic Enhanced Electrochemical Impedance Spectroscopy (FLEEIS) to Determine Battery State of Charge," *Procs. 15th Ann. Batt. Conf.,* Long Beach, CA, Jan 11-14, 2000.
5. Smart Battery System Specifications v.1.1 December 11, 1998 http://www.sbs-forum.org
6. BQ 2060 Data Sheet, Texas Instruments, Inc., 12500 TI Boulevard, Dallas, Texas 75243 http://www.ti.com
7. PS 331 Data Sheet, Power Smart, Inc., One Research Drive, Shelton, CT 06484 http://www.powersmart.com
8. B. Kosko, "Fuzzy Engineering", pp. 41-128 Prentice Hall, NY (1997)
9. Model Technology, Inc., 10450 SW Nimbus Ave., Bldg. R, Portland, OR 97223
10. Lucent Technologies, Corporate Headquarters, 600 Mountain Avenue, Murray Hill, NJ 07974 http://www.lucent.com