Atmel's ATmega406 AVR Microcontroller Provides Full Smart Battery and Battery Protection Functionality for 2 – 4 Li-ion Cells in a Single Chip

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Summary

Previous implementations of intelligent battery protection have typically required at least two chips to perform the various tasks required which include: voltage regulation, battery monitoring, battery protection, charge management, and communication with the host application. Often a third chip has been required to store parameters specific to the particular battery. Battery packs must shrink in size along with the other components of battery-powered applications. However, when accelerating this shrink, a 3-chip solution obviously creates a PCB space problem.

The ATmega406 meets all the application's demands, reducing space, design complexity, and ultimately cost. It includes an AVR® microcontroller with dedicated analog to digital converters tailored for battery fuel gauging and voltage monitoring. Also included are stand-alone high voltage battery protection circuitry, a voltage regulator capable of running the chip on a supply varying from 4 to 25 Volts, integrated cell balancing FETs, and special high voltage I/O capable of controlling charge and discharge. Advanced analog design provides the ATmega406 with unmatched on-chip voltage reference accuracy, resulting in the first single-chip smart battery implementation on the market for 2 – 4 Li-ion cells. With 40 KB of self-programmable Flash program memory, the ATmega406 is capable of in-field firmware upgrades without the need for external programming hardware. Battery parameters can be stored in the internal 2 KB EEPROM. This mix of features makes the ATmega406 AVR capable of implementing a full PC battery pack.

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Introduction

The demand for portable applications such as laptop PCs, cell phones, and digital cameras is ever-increasing. These applications keep getting smaller and more advanced with tougher price competition every day. No application component can escape these toughening requirements, and the vital application power source, the battery, is certainly no exception. Battery capacity development is lagging behind the increasing demands from the application and control of the chemical reaction inside the battery is subject to severe safety requirements, making it difficult to push the limits of the chemical technology. To make life even more difficult for battery vendors, the battery is expected to shrink in size and price along with the rest of the application.

Advanced battery packs, or smart batteries, contain a quite large amount of electronic components. This includes fail-safe circuitry to ensure that the battery cell is not damaged or dangerous to the user; monitoring capabilities and logic to interpret battery conditions and estimate charge left depending on battery load; and communication with the host application. Current smart battery applications are implemented using at least two ICs: a microcontroller for battery management and an analog front-end to ensure battery protection and measurements. In addition, some require a third chip, an EEPROM containing data specific to the battery chemistry, necessary for charge left estimation and other monitoring parameters. These solutions are costly and take up board space.

This document introduces Atmel's ATmega406 smart battery solution, the first single-chip implementation on the market. In a single die, the ATmega406 includes a powerful AVR MCU, a voltage regulator capable of being powered directly from the battery pack, analog to digital converters custom tailored for battery monitoring, high voltage charge and discharge FET drivers, cell balancing capabilities, and independent battery protection circuitry. This true one-chip solution saves design cost and PCB space in addition to broadening the functionality of the smart battery application. With the accuracy of the ATmega406, battery vendors will be able to predict the charge status of the battery more accurately. The better the knowledge of the battery cell, the more it can be allowed to be depleted before reaching the level where the cell itself starts to be damaged. This effectively increases actual battery capacity.

The ATmega406 features innovative high voltage technology in a cross process, which greatly helps reduce the total part count in the system. It's internal voltage regulator enables it to operate on any voltage from 4 to 25 Volts. The analog to digital converter input channels can measure battery cell voltages 25 Volts above Ground, eliminating an external high voltage analog front-end. The device also features three internal FET drivers capable of outputting 25V levels, so no external FET drivers are required.

The battery monitoring capabilities of the ATmega406 are custom tailored to smart batteries. The 12-bit Voltage ADC with ±1 LSB max error provides very good cell voltage measurements. The dedicated fuel gauging Coulomb Counter ADC provides continuous current monitoring with up to 18-bit resolution and very high accuracy. The high accuracy of the ATmega406 battery monitoring is made possible by the innovative on-chip voltage reference with ±0.1% error after calibration. The very accurate voltage and current measurements make it possible to estimate the charge left in the battery very accurately, allowing the application to draw more energy from the battery. One reason for this is that the Li-ion cell is damaged if depleted below a certain voltage level. If this level is reliably known, it is safe to allow depletion very close to this level without risking cell damage. The second reason is the end-user's requirements. Under no circumstances must a laptop PC power off without allowing the user to save his changes and shut down his applications. If the battery pack's state-of-charge is reliably known, it is possible to push the safe limit further towards depletion. With less refined measurement equipment, a guardband must be inserted into the estimate to ensure that the user will be able to shut down reliably. This guardband represents energy that could be used if the estimate really were to be trusted. ATmega406 supplies the required accuracy to make use of this energy.

In a smart battery it is not enough just to monitor its state of charge. Battery management and battery protection is also needed. The ATmega406 takes care of all these functions. The battery's charge and discharge state can be controlled by the microcontroller itself using the integrated high voltage FET driver outputs. Individual cell voltages can be balanced against each other using the internal cell balancing FETs. If the battery finds itself in a dangerous state such as short-circuit or over-current, automatic protection circuitry independent of the MCU will kick in to contain the problem.

The ATmega406 is fully in-field upgradeable through the Two Wire Interface (I2C compatible), making it possible to update its software from the PC in which the battery pack is installed. The on-chip debug system has full access to all features on the chip, making it easy to do software development.

Care has been taken to tune the power consumption of all modules within the chip to a minimum, fulfilling the ATmega406 as a perfect match for any battery powered application.

High voltage technology

Rechargeable Li-ion battery cells typically have a low current capability. For applications where high instant energy is needed, this problem is overcome by using many cells in series. This results in a higher voltage allowing a higher energy with a lower current. The higher voltage is a problem for standard semiconductors as these typically can handle voltages between 2-5 Volts. Smart battery vendors solve the high voltage Input/Output problem by using separate driver circuits.

High Voltage I/O

For battery monitoring and management devices several high voltage inputs and outputs are needed:

- Input to voltage regulator. This input provides power to the device drawn directly from the battery, in the range of 4-25V.
- Input to Voltage ADC for individual cell voltage measurements
- Input to detect the presence of a battery charger
- Outputs to charge, discharge, and pre-charge FETs

Atmel's high voltage technology makes it possible to integrate Flash program memory and logic as well as accurate analog circuitry on the same die as high-voltage tolerant I/O. The ATmega406 is 25 Volt tolerant, making it apt for Li-ion battery packs up to four cells.

Voltage Regulator

Modern semiconductors typically run at power supply in the range 2 to 5 Volts. A battery supplying up to 25 Volts can thus not source the semiconductor directly. The ATmega406 chip is powered directly from the battery through the internal voltage regulator. The input is allowed to vary from 4 to 25 Volts. This voltage is regulated down to 3.3V internally, which is a suitable level for the internal logic, low voltage I/O lines, and analog circuitry.

To minimize power consumption during inactive periods, the voltage regulator contains a power consumption control module. When the chip enters low power modes, the voltage regulator will reduce the consumption in the regulator itself, further contributing to low power consumption.

An external decoupling capacitor of 1 µF or larger is required for stable operation of the Voltage Regulator. A larger capacitor will allow larger load currents but will increase start-up time.

Battery Monitoring

Parameters such as individual cell voltages, current flowing into or being drawn from the battery, and other variables such as battery pack temperature are essential to keep track of in the smart battery application. ATmega406 has the tools required to monitor all the necessary parameters.

Voltage Measurements

Many voltage sources need to be monitored in a smart battery. Inidividual cell voltages require differential ADC measurements. To adjust the level of the measured cell voltage to that of the ADC, either an internal or an external gain is needed. Single-ended channels are necessary to measure other parameters such as the regulated voltage, and temperature at various locations inside the battery pack.

The ATmega406 has a 10-channel, 12-bit Sigma/Delta ADC for voltage measurements (V-ADC). The four differential channels for cell voltage measurements are scaled 0.2x to comply with the full scale range of the V-ADC. In addition there are six single ended channels referenced to signal Ground. One channel is for measuring the internal die temperature sensor, four channels for measuring the pins at port A for cell temperature monitoring, and one channel for measuring the internal regulated voltage VREG. The VREG input is also scaled 0.2x to comply with the Full Scale range of the V-ADC.

To obtain a total absolute accuracy better than ± 0.25% for the cell voltage measurements, calibration registers for the individual cell voltage gain in the analog front-end are provided. A factory calibration value is stored in each register, and a V-ADC conversion of a cell voltage is scaled with the corresponding calibration value by software to correct for gain error in the analog front-end.

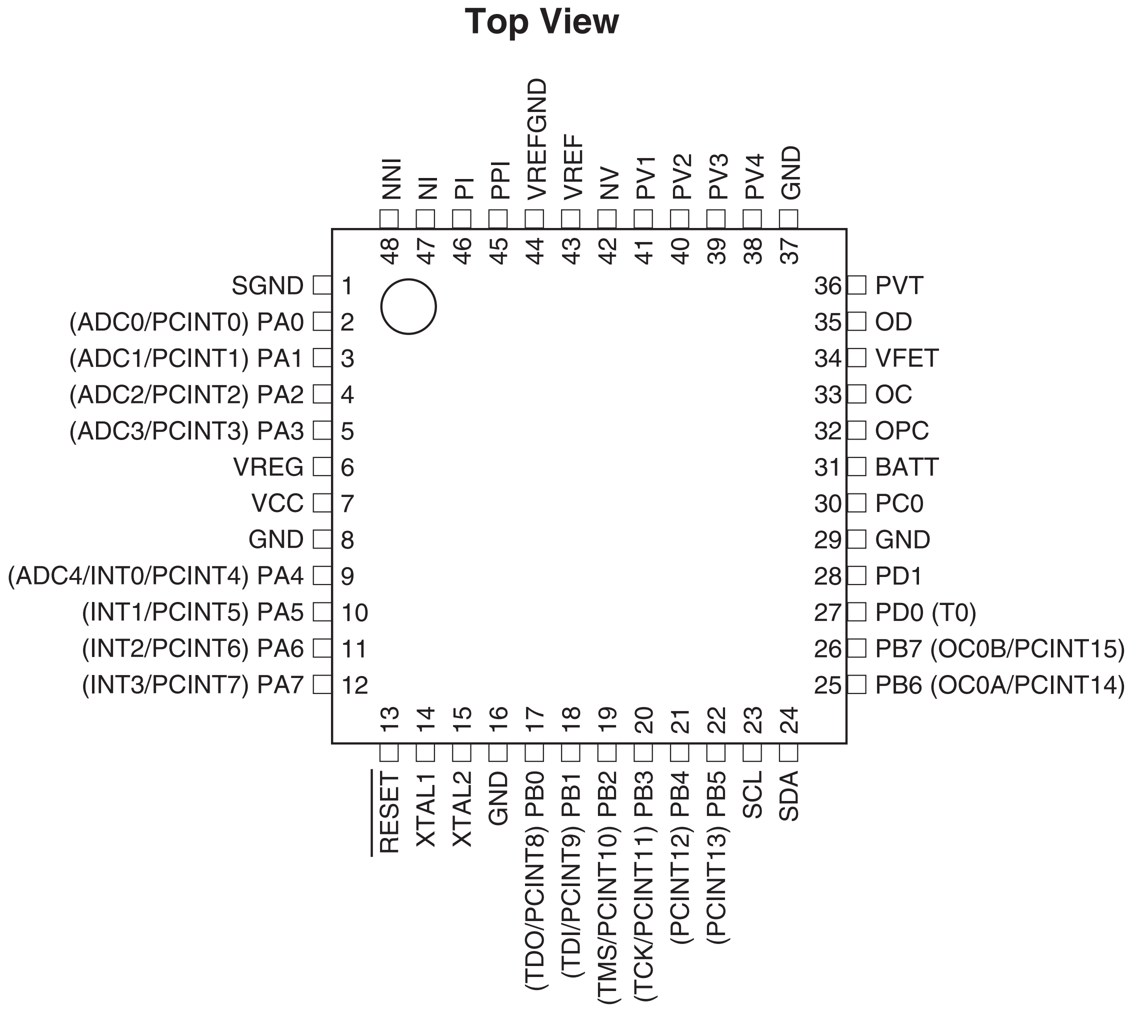

Figure 1. ATmega406 Pin-out

Counting Electrons

A PC battery pack is under constant abuse; it is constantly being depleted and then recharged at several levels of load. The smart battery is expected to tell how long it will be able to sustain the current load before it's depleted at any given time. In order to provide this service to the end user, the battery needs to know exactly how much energy has been drained from the battery so that this amount can be deducted from the full charge capacity of the pack. Once the remaining battery capacity is determined, the charge left algorithm can estimate the time left on the existing load. Calibration at various voltage points on the charge curve is not accurate enough; the smart battery has to actively log and count current charged into and discharged from the battery.

The ATmega406 features a dedicated Sigma-Delta ADC (CC-ADC) optimized for Coulomb counting to sample the charge or discharge current flowing through the external sense resistor. Two different output values are provided: instantaneous current and accumulate current. The instantaneous current output has a short conversion time at the cost of lower resolution. The accumulate current output provides a highly accurate current measurement for Coulomb counting.

- Low power Sigma-Delta ADC optimized for Coulomb counting
- Instantaneous current output with 3.9 ms conversion time
- Accumulate current output with programmable conversion time: 125, 250, 500 or 1000 ms
- Input voltage range larger than ± 0.15V, allowing measurement of more than ± 30A @ 5 mΩ sense resistor
- 53.7 µV resolution (10.7 mA @ 5 mΩ) for instantaneous current output
- 3.35 µV resolution (0.67 mA @ 5 mΩ) for accumulate current output
- Input offset less than 10 µV for the ADC
- Interrupt on instantaneous current conversion complete
- Interrupt on accumulate current conversion complete
- Interrupt on regular current with programmable compare level and programmable sampling interval: 250, 500, 1000 or 2000 ms

The sampling Coulomb Counter provides a highly accurate and flexible solution. Accuracy can easily be traded against conversion time. It also provides Regular Current detection. This allows ultra-low power operation in Power-save mode when small charge or discharge currents are flowing.

The Accumulate Current output is a high-resolution, high accuracy output with programmable conversion time. The converted value is an accurate measurement of the average current flow during one conversion period. The CC-ADC generates an interrupt each time a new Accumulate Current conversion has finished if the interrupt is enabled.

While the CC-ADC is converting, the CPU can enter sleep mode and wait for an interrupt from the Accumulate Current conversion. After adding the new Accumulate Current value for Coulomb Counting, the CPU can go back to sleep again. This reduces the CPU workload, and allows more time spent in low power modes, reducing power consumption

The CC-ADC can generate an interrupt if the result of an Instantaneous Current conversion is greater than a programmable threshold. This allows the detection of a Regular Current condition. This allows an ultra-low power operation, where the CC-ADC can be configured to enter a Regular Current detection mode with a programmable current sampling interval. The Coulomb Counter will repeatedly do one Instantaneous Current conversion, before it is turned off for a timing interval specified by the user software. This allows operating the Regular Current detection while keeping the Coulomb Counter off most of the time.

Internal Voltage Reference and Temperature Sensor

The very high accuracy of the V-ADC and CC-ADC would not be possible without an extremely stable voltage reference. The ATmega406 features a very accurate 1.1 V internal voltage reference, which achieves ± 0.1% accuracy after calibration.

- Accurate voltage reference at 1.100 V
- ± 0.1% accuracy after calibration (2 mV calibration steps)
- Temperature drift less than 80 ppm/°C after calibration
- Alternate low power reference for voltage regulator
- Low power consumption

To guarantee ultra low temperature drift after factory calibration, ATmega406 features a two-step calibration algorithm. The first step is performed at 85°C and the second at room temperature. By default, Atmel factory calibration is performed at 85°C, and the result is stored in Flash. The customer can easily implement the second calibration step in their test flow. This requires an accurate input voltage and a stable room temperature. Temperature drift after this calibration is guaranteed by design and characterization to be less than 80 ppm/°C from 0°C to 60°C and 100 ppm/°C from 0°C to 85°C. The calibration register can also be altered runtime to implement temperature compensation in software.

Internal Temperature Sensor

ATmega406 has an On-chip temperature sensor for monitoring die temperature. A voltage proportional to absolute temperature, VPTAT, is generated in the voltage reference circuit and connected to the multiplexer at the V-ADC input. This temperature sensor can be used for runtime compensation of temperature drift in both the voltage reference and the On-chip Oscillator.

Battery Management

In its fullest implementation, the smart battery will not only monitor battery parameters. It will also manage the environment of the battery pack according to these parameters. An ATmega406-based battery pack can be made to implement battery charging algorithms, cell balancing, and communication with the host application.

FET Control

In addition to the FET disable control signals from the battery protection circuitry, the CPU may disable the Charge FET (C-FET), the Discharge FET (D-FET), or both. Note that the CPU is never allowed to enable a FET that is disabled by the battery protection circuitry.

The PWM output from the 8-bit Timer/Counter0 can be configured to drive the C-FET, Precharge FET (PC-FET) or both directly. This can be useful for controlling the charging of the battery cells.

If the battery has been deeply discharged, large surge currents may result when a charger is connected. In this case, it is recommended to first pre charge the battery through a current limiting resistor. For this purpose, ATmega406 provides a Precharge FET (PC-FET) control output. This output is enabled by default.

Cell Balancing

The ATmega406 incorporates cell-balancing FETs. The chip provides one cell balancing FET for each battery cell in series. The FETs are directly controlled by the application software, allowing the cell balancing algorithms to be implemented in software. The FETs are connected in parallel with the individual battery cells.

SMBus™

In the PC battery pack application, SMBus (System Management Bus) is the standard for communication with the PC. The ATmega406 features a two-wire serial interface compatible with the SMBus standard.

- Simple yet powerful and flexible communication interface, only two bus lines needed
- Both Master and Slave operation supported
- Device can operate as transmitter or receiver
- 7-bit address space allows up to 128 different slave addresses
- Multi-master arbitration support
- Operates on 4 MHz clock, achieving up to 100 kHz data transfer speed
- Slew-rate limited output drivers

- Noise suppression circuitry rejects spikes on bus lines
- Fully programmable slave address with general call support
- Address recognition causes wake-up when AVR is in sleep mode

The SMBUS interface can be used to upgrade the program code using the AVR's self-programming capabilities. See "In-field updates" below for details.

Battery Parameters

The ATmega406 features a 512 Byte EEPROM for data storage. It is organized as a separate data space, in which single bytes can be read and written. This data space is intended for storage of key parameters vital to the battery application.

Battery Protection

A Li-ion battery cell is essentially a volatile chemical reaction packaged inside a cylinder. A lot of potential energy is stored in each cell, and if the battery is exposed to conditions outside of its specifications the cell could catch fire or explode. Obviously, this cannot be allowed to happen under any circumstances, so the battery needs to be protected against all potentially damaging conditions. The automated battery protection circuitry inside the ATmega406 monitors the battery voltage and charge/discharge current to detect illegal conditions and protect the battery from these when required.

- Deep Under-voltage Protection
- Charge Over-current Protection
- Discharge Over-current Protection
- Short-circuit Protection
- Programmable and Lockable Detection Levels and Reaction Times
- Autonomous Operation Independent of CPU

If the voltage at the battery's positive pole falls below the programmable Deep Under-voltage detection level, the Charge-FET, Precharge-FET and Discharge-FET are disabled and the chip is set in Power-off mode to reduce power consumption to a minimum.

The Current Battery Protection circuitry (CBP) monitors the charge and discharge current and disables C-FET, PC-FET, and D-FET if an over-current or short-circuit condition is detected.

The activation of a protection also issues an interrupt to the CPU. The battery protection interrupts can be individually enabled and disabled by the CPU.

Deep Under-voltage Protection

The Deep Under-voltage Protection ensures that the battery cells will not be discharged deeper than the programmable Deep Under-voltage detection level. If the voltage at the VFET pin is below this level for a time longer than the programmable delay time, C-FET, PC-FET and D-FET are automatically switched off and the chip enters Power-off mode.

The device will remain in the Power-off mode until a charger is connected. When a charger is detected, a normal power-up sequence is started and the chip initializes to default state.

Discharge Over-current Protection

The Current Battery Protection (CBP) monitors the cell current by monitoring the shunt resistor voltage at the PPI/NNI input pins. A differential operational amplifier amplifies the voltage with a suitable gain. The output from the operational amplifier is compared to an accurate, programmable On-chip voltage reference by an Analog Comparator. If the shunt resistor voltage is above the Discharge Over-current Detection level for a time longer than Over-current Protection Reaction Time, the chip activates Discharge Over-current Protection.

When the Discharge Over-current Protection is activated, the external D-FET, PC-FET, and C-FET are disabled and a Current Protection Timer is started. This timer ensures that the FETs are disabled for at least one second. The application software must then set the DFE and CFE bits in the FET Control and Status Register to re-enable normal operation. If the D-FET is re-enabled while the loading of the battery still is too large, the Discharge Over-current Protection will be activated again.

Charge Over-current Protection

If the voltage at the PPI/NNI pins is above the Charge Over-current Detection level for a time longer than Over-current Protection Reaction Time, the chip activates Charge Over-current Protection.

When the Charge Over-current Protection is activated, the external D-FET, PC-FET, and C-FET are disabled and a Current Protection Timer is started. This timer ensures that the FETs are disabled for at least one second. The application software must then set the DFE and CFE bits in the FET Control and Status Register to re-enable normal operation. If the C-FET is re-enabled and the charger continues to supply too high currents, the Charge Over-current Protection will be activated again.

Short-circuit Protection

A second level of high current detection is provided to enable a fast response time to very large discharge currents. If a discharge current larger than the Short-circuit Detection Level is present for a period longer than Short-circuit Reaction Time, the Short-circuit Protection is activated.

Secure Parameter Storage

The Battery Protection parameters set in the Battery Protection Parameter Registers and the disable function set in the Battery Protection Disable Register can be locked from any further software updates. Once locked, these registers cannot be accessed until the next hardware reset. This provides a safe method for protecting these registers from unintentional modification by software runaway. It is recommended that software sets these registers shortly after reset, and then protects these registers from any further updates.

Power Consumption

To avoid damaging the battery cells during long-term storage, it is important for the battery itself to consume as little power as possible. The single chip implementation helps reduce system power consumption by eliminating external components and collecting all functionality in one single package. In addition, the ATmega406 features various low-power modes called sleep modes. Sleep modes enable the application to shut down unused modules in the MCU, thereby saving power. The ATmega406 provides four sleep modes allowing the user to tailor the power consumption to the application's requirements:

- **Idle Mode**, in which the CPU is stopped but all peripheral functions continue operating.
- **ADC Noise Reduction Mode**, which improves the noise environment for the ADC while saving power. If the V-ADC is enabled, a conversion starts automatically once this mode is entered.
- **Power-save Mode**, in which the fast RC oscillator is stopped. Only the battery protection circuitry and slow oscillators are kept running, as well as the CC-ADC for current measurements.
- **Power-down Mode**, in which all clocks are halted. Battery protection, a Watchdog or external interrupt, or an SMBUS address match can wake up the device.
- **Power-off Mode** makes the CPU ask the voltage regulator to shut off power to the CPU, leaving only the regulator and the Charger Detect circuitry to be operational. This is the mode the ATmega406 uses to ensure that the battery cells are not damaged if the voltage is too low.

The table below shows some key typical power consumption figures for the ATmega406.

Condition	**Current draw**
Active 1 MHz	1.2 mA
Idle 1 MHz	0.6 mA
Power-save	90 µA
Power-down	20 µA
Power-off	2 µA

Table 1. Key Power Consumption Figures for ATmega406

Application Development and Updating

A Li-ion battery pack is an important component in any system, and it is imperative that it functions correctly. It is important that the smart battery software can be updated in the field in case of safety-related improvements or bug fixes. In order to test all possible safety scenarios on actual battery hardware, it is also important to have debug capabilities compatible with the final hardware.

In-field Updates

The PC battery pack is a relatively expensive application where safety is key. This makes it important to be able to update the application code in the product at a minimum cost should any bug or improvement be discovered. In-field updates provide the most flexible and inexpensive solution since the end user is not required to return the application to the factory or service location. Equipping the battery pack with in-field update capabilities presents a number of challenges to the system designer, the most notable being ensuring safety during updates. In the battery application, the core application cannot be halted as it is required to monitor and manage the electrical end of the chemical reaction in the battery at all times. Because of this, a regular in-system programming interface cannot be used.

The ATmega406 facilitates safe in-field update through self-programming. The ATmega406 CPU can access and write its own program memory. Atmel's self-programming has true read-while-write capabilities, so critical parts of the battery application can be allowed to remain running while the update is in progress. Since the programming is CPU-initiated, the device is able to receive updates through any supported interface. This means that the SMBUS interface between the PC and battery in effect can be used for in-field updating of the battery. This is by far the most flexible option, as the update can be implemented as a program running on the host PC.

On-chip Debugging

The ATmega406 is a highly integrated application-specific device with complex analog characteristics. It is important for the designer to be able to develop and debug the battery application in the assurance that the responses seen while debugging will match exactly those of the final application. For this purpose, the ATmega406 features an on-chip debugging system accessible through the IEEE std. 1149.1 JTAG interface. The OCD system has full access to all internal peripheral units, the internal register file, and all memories. The debugging is controlled from Atmel's AVR Studio® 4 debugging software through the JTAG ICE on-chip debug interface.

Typical Operating Circuit

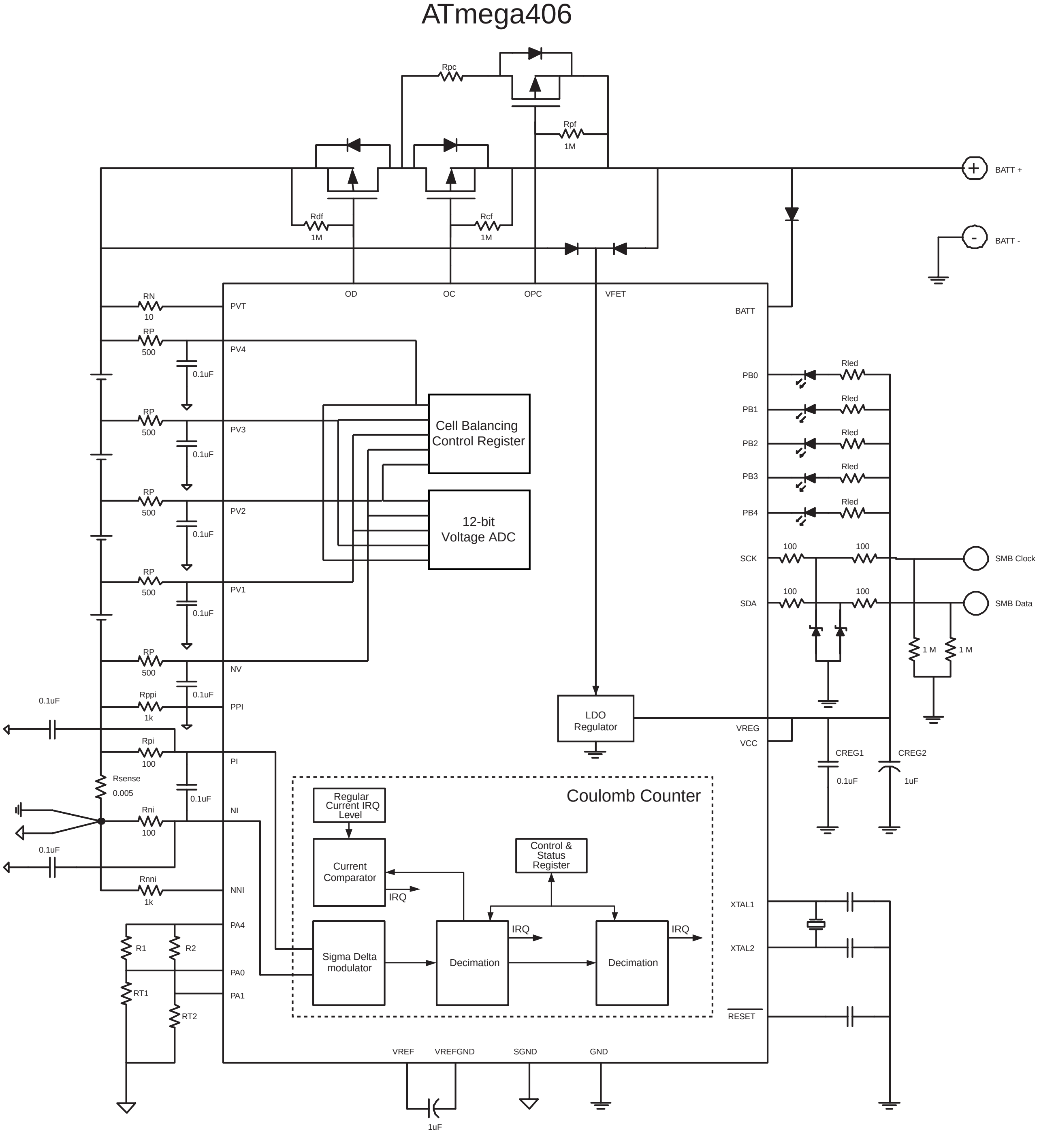

Figure 2. Typical operating circuit

Development Tools

A wide range of development tools supports the ATmega406 device.

Starter Kits and In-system Programmers

ATAVRSBKIT is a development kit containing all the necessary hardware to implement a full smart battery application. The kit is intended for use with the JTAGICE mkII programmer and debugger tool.

JTAGICE mkII serves as the in-system programming tool for ATmega406. This low-cost tool is typically used for development when the target hardware is ready, and as service tool for field upgrades of the final product.

High Level Language Compilers

A broad range of high-level language compilers supports the AVR Family, and the ATmega406 is no exception.

C-compilers

Four C-compilers dominate the market for the AVR. The compilers have different cost and performance points. These compilers are: IAR **Embedded Workbench**® by IAR System AB®, **ICCAVR**™ by Imagecraft Creation Inc™, **CodeVisionAVR™** by HP InfoTech S.R.L., and **GNU AVRGCC**, which is an open source compiler. All these compilers support or will support the mega48/88/168. There are also compilers available for EC++ and micro C.

Other Compilers

For engineers not used to writing in C, there are many other High-Level language compilers available. These include but are not limited to: **Pascal** by E-lab Computers; **Basic** and Bascom from MCS Electronics®, Digimok and Microdesign; **Forth** by Forth Inc.

Simulators and Emulators

AVR Studio® from Atmel supports simulation of the ATmega406. In addition, **C-spy**® from IAR System AB and **VMLAB** from Advanced Micro Tools support the devices.

The low cost **JTAGICE mk-II** supports the ATmega406. JTAGICE mkII supports full emulation of analog and digital features, Assembly and High-level language symbolic debugging, and Program breakpoints.

Production Programmers

A broad range of production programmers, including both in-system and parallel programming interfaces, supports the AVR family. Support for the ATmega406 in different package types are added on request from customers.

Editor's Notes

About Atmel Corporation

Atmel is a worldwide leader in the design and manufacture of microcontrollers, advanced logic, mixed-signal, nonvolatile memory and radio frequency (RF) components. Leveraging one of the industry's broadest intellectual property (IP) portfolios, Atmel is able to provide the electronics industry with complete system solutions. Focused on consumer, industrial, security, communications, computing and automotive markets, Atmel ICs can be found Everywhere You Are℠.

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