Micro Power Battery State-of-Charge Monitor

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Abstract — *This paper presents the design and implementation of a micro power battery state of charge monitor. The novelty of this design lies in the extreme low power consumption and accurate prediction of the battery reserve time. The average current drawn is successfully limited to 60 µA, which is significantly smaller than those in currently available devices. The proposed design predicts the reserved battery charge with an accuracy of 5% under different discharge conditions. The automated learning scheme using software is utilized. Protection of the battery against excessive current drain and usage outside the specified temperature range is incorporated.*

This paper details the proposed technique adopted for power reduction. The battery temperature and current sensing circuits are normally in power down mode, they go into active mode for the microcontroller to take measurements. An ON/OFF ratio of 1:153 is achieved which results in power reduction by a factor of 59.30. The average current requirement of the proposed design is reduced from 3302.79 µA to 55.69 µA with the adoption of power reduction approach. The proposed design has been tested on a NiMH, NiCd and Li-Ion battery packs and the experimental results confirm the utility of the proposed design[1].

Index Terms — Battery gas gauging, battery state-of-charge, battery reserve time, reserved battery charge.

I. INTRODUCTION

The use of rechargeable batteries has been rapidly increasing these days. They are finding application in the areas like cellular phones, portable electrical and electronic appliances, portable computers and note books, communication and medical equipment. This need of portability expects the batteries to work in different environment, with varying operating temperature conditions and also under varied rate of charge or discharge conditions. It has been the interest of the user to precisely know the reserved battery charge and the time for which the battery charge will survive or last in the existing operating environment.

The battery state of charge is significantly influenced by temperature, charge/discharge rate [1], cell ageing and self discharge; as such the technique or the algorithm for predicting the status of battery charge has to consider these parameters to arrive at an accurate result. The increasing use of batteries in mobile application areas and the need to improve the battery reserve time has also resulted in the development of low power design techniques [2]-[4]. The effort in the literature had been to design power efficient circuits for enhanced battery usage time [5]-[7]. Low power devices are now available and the designs using these devices have been successful in reducing the power consumption.

In this paper, we focus on the development of an accurate micro power battery state of charge monitoring circuit by using the commercially available low power devices.

A. Prior Work

The area of battery gas gauging has been receiving considerable attention and several models have been developed to estimate the battery state of charge. Recent effort in the literature has been to optimize the measurement techniques, so as to improve the accuracy of estimating the available battery charge. Battery monitoring ICs are also available that conduct current, temperature and voltage measurements on the battery for charge prediction, but low accuracy (typically 20%), limited on chip processing and analysis capability of these devices limit their usage. The currently used techniques for battery gas gauging are based on voltage measurement and accumulation of current measurements [8]. The accuracy with which the state of charge can be estimated and the cost of implementation has been a major concern in the designs proposed in the literature [9], [10], [13], [19].

A microprocessor based estimator (with an accuracy of 1%) for detecting the state of charge in a battery is proposed in [9], but this has high cost of realization. The state of charge estimated over a wide operating range and battery conditions is described in [10]. This design is of low complexity which achieves an accuracy of 10%. Authors in [11] describes a cost effective solution to battery gas gauging based on coulomb counting technique and takes advantage of capacity learning methods. Another approach by combining the monitoring of battery temperature, voltage and charge/discharge rate is described in [12], [15]. A microcontroller is used to decide the best time to terminate charging and to determine the state of charge of a NiMH battery for a laptop application. Reference [13] describes an analytical expression for predicting the remaining capacity of a battery. An accuracy of 5% between simulated and predicted data is reported. A mathematical model to estimate the battery available capacity, considering the ageing and temperature effects, and under variable discharge current conditions is detailed in [14].

The development of battery state of charge monitoring has also been reported in several US patents. Authors in [16] describe a battery management system loaded into a notebook computer and provide the method for monitoring and viewing the capacity of a battery while in use. The design [17] presents full capacity determination based on measuring open circuit

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voltage of the battery cell and correlating such measurements for full capacity calculations. A battery monitor system [18] provides information indicating the remaining capacity of a battery to the user. Instantaneous battery voltage, current and battery temperature are measured to indicate the remaining capacity according to a predetermined algorithm.

We have noted that the effort in the literature [8], [9], [12], [14]-[19] have been to establish design techniques for efficient and accurate estimation of battery state of charge. Models to estimate battery state of charge under different charge or discharge conditions are reported. However, these approaches, specifically do not address the power requirement of the monitoring circuit used for estimation of the battery charge for NiMH/NiCd or Li-Ion batteries and they do not predict the discharge reserve time, which is of high interest to the user, rather than battery capacity in percentage.

B. Proposed Design

This paper focuses on the design of a battery state of charge monitor. The goal of the proposed design is to minimize the power requirement of the monitoring circuit and to provide an accurate estimate of the reserved battery charge while the battery is being charged or is under discharge. The measurement and the monitoring procedure implemented precisely depend on measuring the charge. The proposed design addresses the effects of temperature and ageing on the battery. The microcontroller measures the battery voltage, temperature and charge/discharge current. The measurement data is corrected for the temperature, charge/discharge rate and battery chemistry (NiMH, NiCd or Li-Ion) in order to arrive at an accurate estimate of discharge reserve time. The proposed design has been tested for NiMH/NiCd/Li-Ion batteries and the approach can be applied to other batteries.

Key Design Features

- Prediction of battery reserve time in minutes. The algorithm predicts the reserved battery charge with an accuracy of 5%;
- Common code structure for prediction of discharge reserve time for NiCd, NiMH or a Li-Ion battery;
- An external access to the measured parameters through a 3 – wire serial interface. The data transfer can be carried out at user selectable baud rate, without the need of initial synchronization or setup phase;
- The design reduces the average current consumption of the measurement circuit from 3302.79 µA to 55.69 µA. Power consumption reduced by a factor of 59.30. This is 12.84% in 1 year for a battery of 3800 mAH capacity;
- Incorporating learning capability in the design. The battery capacity is automatically recalibrated in the course of a discharge cycle from full to empty battery;
- Implementation of protection features in the battery pack, as preventing the battery usage under out of range temperatures conditions, battery deep discharge protection, and overload protection.

The battery state of charge or discharge reserve time can be displayed on an external display device, which can be accessed via the serial interface. The calculated available charge of the battery is compensated according to the battery temperature, and charge/discharge rate. This ensures that the indicated charge status is always a conservative representative of the charge available for use under the given usage conditions.

C. Organization of the paper

The organization of this paper is as follows; the design concept and functioning details of the gas gauging design are provided in section II. Section III details the software design and hardware details enforced with block diagram and circuit description. The experimental results of the developed prototype design, along with its performance characteristics are provided in section IV. Finally section V summarizes the conclusions from this paper and outlines the future work.

II. DESIGN CONCEPT

A. Battery Charge Monitoring

The prediction of reserved battery charge is accomplished by accurately monitoring the current going into the battery (battery charging) and the current removed from the battery (battery under discharge). This is integrated over time to predict the battery reserve time. The block diagram depicting the connections between battery, load and charger are shown in the figure 1. The load is connected through a current limiting circuit to the battery. The circuit is controlled by a MOSFET switch to introduce a suitable resistor in series with the load, for limiting the current drawn, when the battery voltage falls below a predefined threshold value.

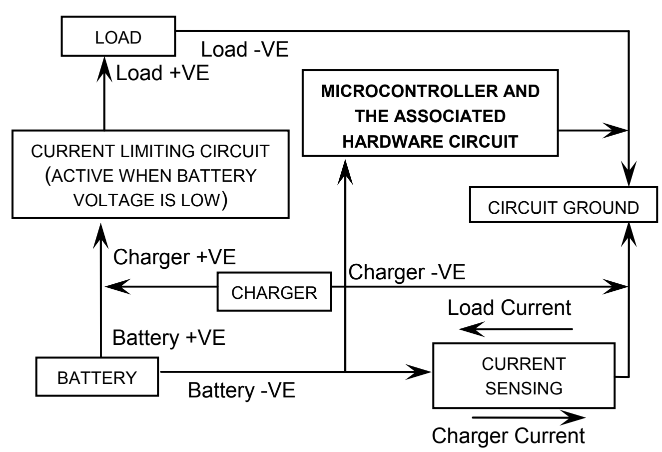

Figure 1: Interconnection between battery, load and the charger

The process of control, monitoring and measurement of the battery parameters is handled by an 8 bit microcontroller, ATtiny26L [21]. The microcontroller accumulates the measured charge, discharge, as well as an estimation of self discharge. The analog measurements carried out to arrive at an accurate estimate of battery charge are: battery charging current; battery discharging current; battery voltage; load voltage and battery temperature. The implemented software logic converts these parameters into the charge status of the battery. Temperature compensation is provided to charge, discharge and self discharge currents. Additionally both charge and discharge currents are also rate compensated. The corrections applied to the measured charge data are illustrated in figure 2 and the corresponding pseudo code implementation for NiMH is detailed in figure 3(a) –3(d). The correction factors for NiMH, NiCd and Li-Ion batteries are stored in the EEPROM and are updated over various charge/discharge cycles through software learning.

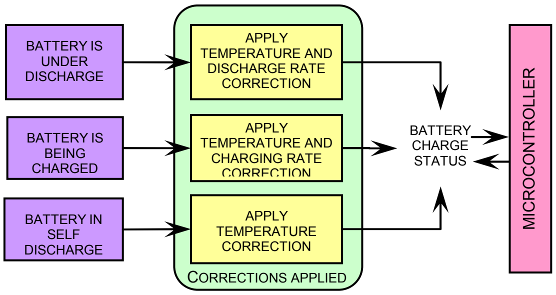

Figure 2: Correction to the measured charge data

B. *Power Reduction Approach*

The measurement of battery parameters by microcontroller is done once every 1000 ms. In order to minimize power consumption; the measurement circuits (temperature and current) are in power down mode for 99.35% of the time and are active for 0.65% of the time. A free running oscillator, with a time period of 1 second is designed to generate wakeup interrupt. On wakeup, the controller powers the measurement circuits, allows the circuit voltages to stabilize for battery measurements to be carried out. The timing details of the implemented measurement approach are explained in figure 4.

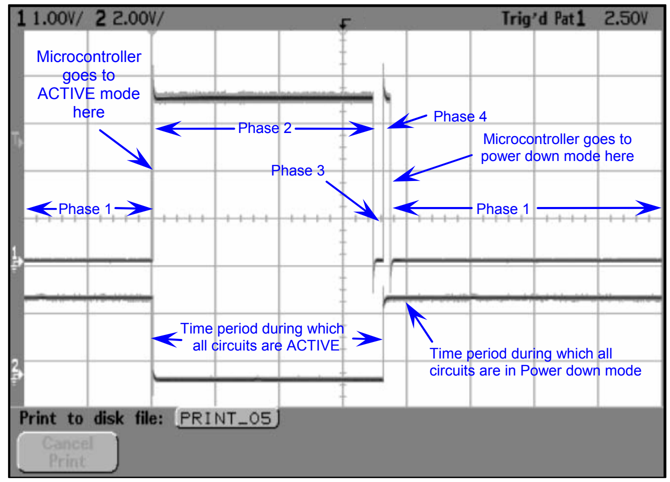

Figure 4: The power reduction approach

```
DISCHARGE COMPENSATION FACTOR = 100;
IF (DISCHARGE CURRENT ≤ 1.5A)
   DISCHARGE COMPENSATION FACTOR = DISCHARGE COMPENSATION FACTOR + 5;
IF (BATTERY TEMPERATURE < 10°C)
{
   DISCHARGE COMPENSATION FACTOR =
      DISCHARGE COMPENSATION FACTOR + ((10 – BATTERY TEMPERATURE) / 2);
}
AVAILABLE CHARGE = AVAILABLE CHARGE –
   (MEASURED CHARGE × DISCHARGE COMPENSATION FACTOR / 100);
```

Figure3a: Code snippet for discharge correction

```
IF (BATTERY TEMPERATURE < 30°C)
   CHARGE COMPENSATION FACTOR = 80;
ELSE IF (BATTERY TEMPERATURE ≥ 30°C && BATTERY TEMPERATURE ≤ 40°C)
   CHARGE COMPENSATION FACTOR = 80 – 1.5 × (BATTERY TEMPERATURE – 30);
ELSE
   CHARGE COMPENSATION FACTOR = 65;
IF (DISCHARGE CURRENT > 1.5A)
   CHARGE COMPENSATION FACTOR = CHARGE COMPENSATION FACTOR + 15;
AVAILABLE CHARGE = AVAILABLE CHARGE +
   (MEASURED CHARGE × CHARGE COMPENSATION FACTOR / 100);
```

Figure3b: Code snippet for charge correction

```
IF (BATTERY TEMPERATURE < 10°C)
   SELF DISCHARGE COMPENSATION FACTOR = 256;
ELSE IF (BATTERY TEMPERATURE ≥ 10°C && BATTERY TEMPERATURE ≤ 70°C)
   SELF DISCHARGE COMPENSATION FACTOR =
      256 / (2 ^ BATTERY TEMPERATURE /10);
ELSE
   SELF DISCHARGE COMPENSATION FACTOR = 2;
AVAILABLE CHARGE = AVAILABLE CHARGE -
   (AVAILABLE CHARGE / SELF DISCHARGE COMPENSATION FACTOR);
```

Figure3c: Code snippet for self discharge correction

```
DISCHARGE COMPENSATION FACTOR = 100;
IF (DISCHARGE CURRENT ≤ 1.5A)
   DISCHARGE COMPENSATION FACTOR = DISCHARGE COMPENSATION FACTOR + 5;
IF (BATTERY TEMPERATURE < 10°C)
{
   DISCHARGE COMPENSATION FACTOR =
      DISCHARGE COMPENSATION FACTOR + ((10 – BATTERY TEMPERATURE) / 2);
}
TIME TO LIVE = AVAILABLE CHARGE /
      (MEASURED CHARGE × DISCHARGE COMPENSATION FACTOR × 60/100);
```

Figure3d: Code snippet for calculating battery life in minutes

In figure 4, the channel 2 depicts the active and power down status of various circuits. The output level 1 indicates that the power regulators for the measurement circuits are in power down mode and an output level 0 indicates that they are in active mode. The circuit remain in active mode for 6.5 ms (maximum time) and in power down mode for 993.5 ms, achieving an ON/OFF ratio of 1:153. The summary of various measurement phases is illustrated figure 5.

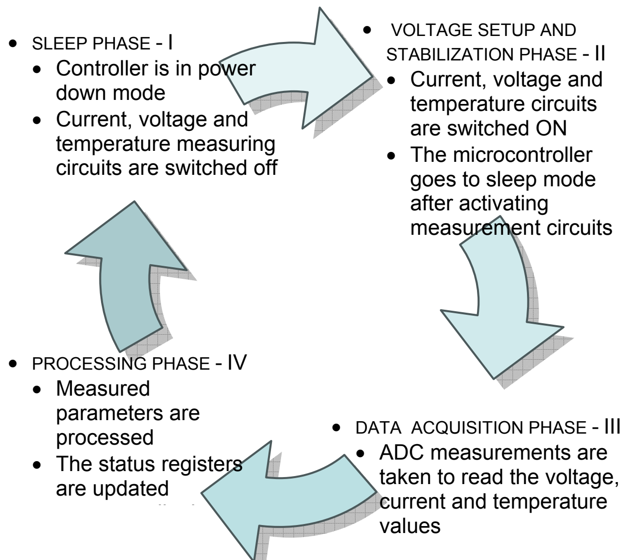

Figure 5: Various phases of measurement

Sleep mode (*phase 1*) – The microcontroller is in power down mode and waits for the wake up signal to start the measurement process. The power to the wake up circuit is always ON and the power regulators for the measurement circuits are in shut down mode. The circuit draws 39.78 μA during this phase.

Voltage setup and stabilization (*phase 2*) – In the phase 2, measurement circuits are powered up and the respective regulators are switched ON. The controller goes to sleep mode immediately after generating a power ON signal to the regulators. A time period of 5.0 ms is allowed for all the voltages to stabilize. The ADC reference voltage also builds up and reaches a stable value during phase 2. The circuit draws 2603.79 μA in this phase.

Data acquisition (*phase 3*) – The circuits switched ON in phase 2 continue to be in active mode during phase 3. The ADC measurements by the microcontroller are initiated and completed in this phase. The results show that a time period of 0.8 ms is needed for the measurement procedure to be completed. During this phase battery current, battery voltages and battery temperature measurements are taken. The circuit draws 3302.79 μA (maximum) current in this phase.

Processing (*phase 4*) – In this phase power regulators for the measurement circuits are put in shut down mode. The microcontroller is active and does processing on the data acquired in phase 3. The measurements results show that the microcontroller completes data processing in a time period of 0.7 ms. The circuit draws 738.78 μA current in this phase.

The microcontroller on completion of phase 4 goes to power down mode and waits for the wake up interrupt to start the measurement procedure once again.

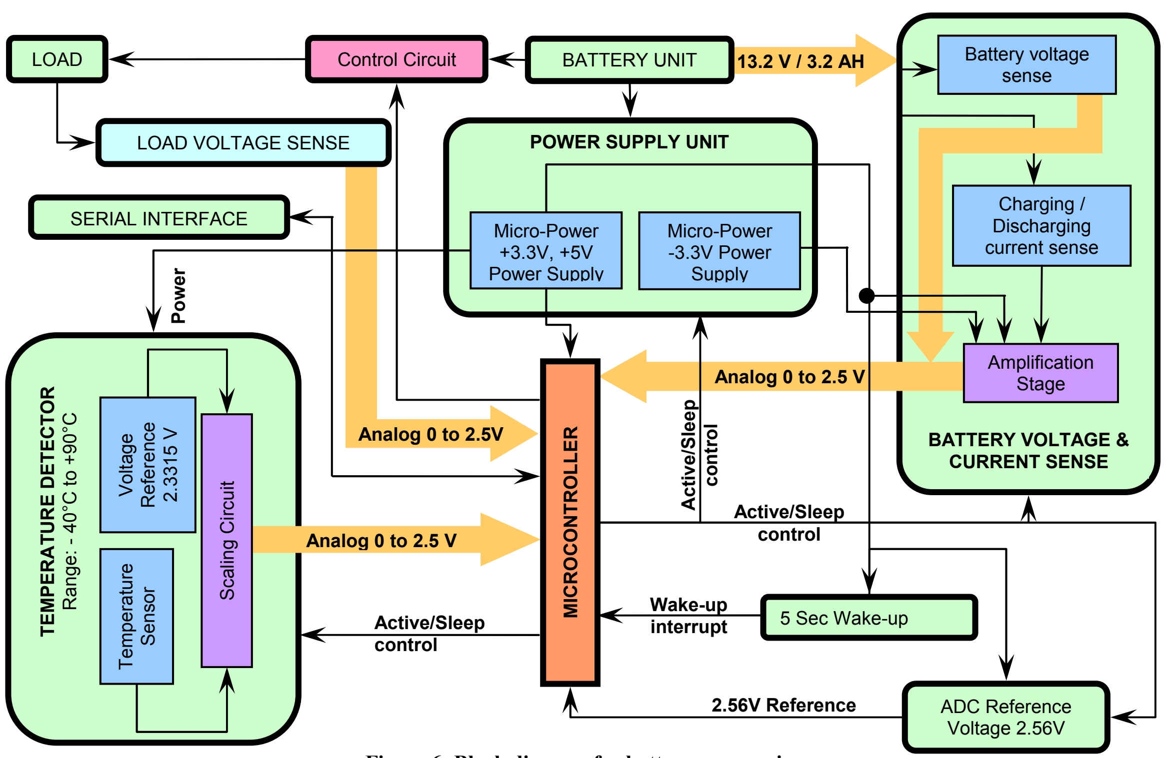

Figure 6: Block diagram for battery gas gauging

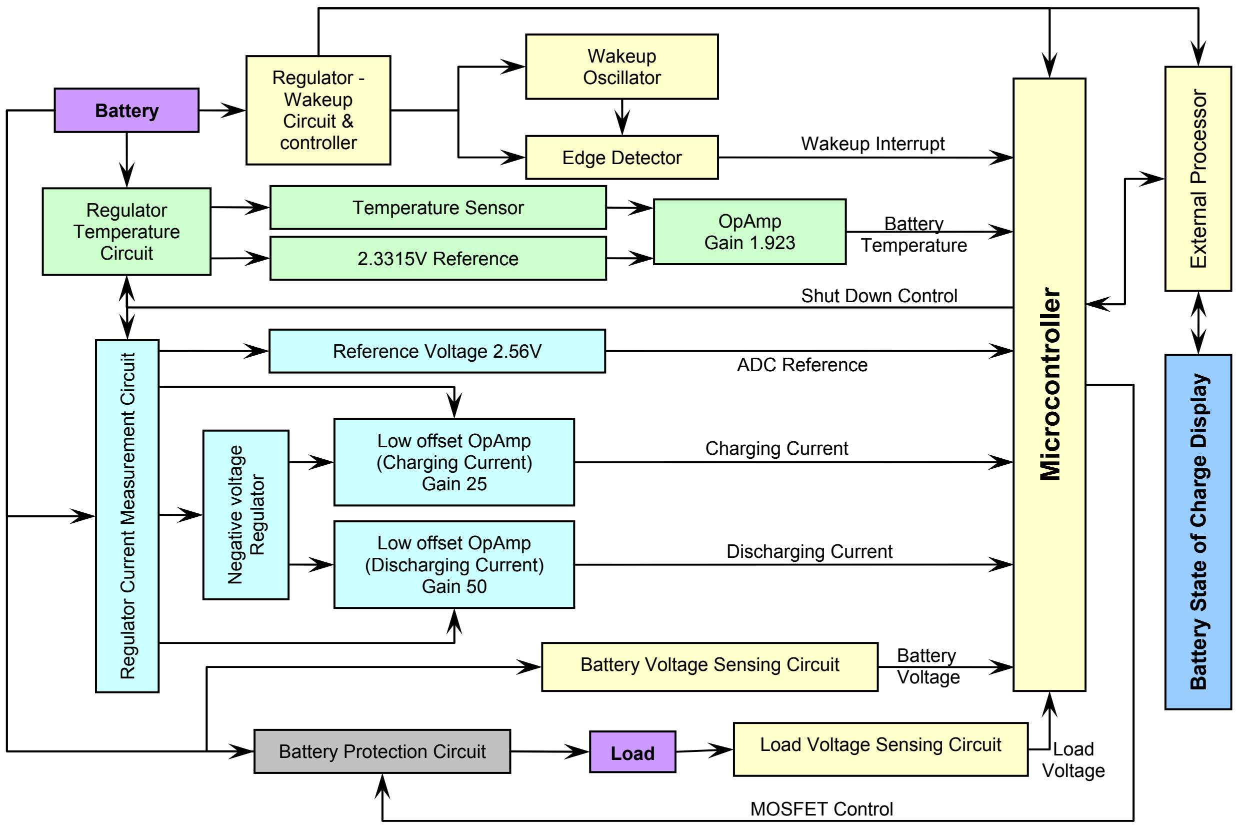

Figure 7: Hardware implementation of the gas gauging design

III. Hardware Design

The block diagram of the gas gauging design is shown in the figure 6 and the hardware implementation is shown in the figure 7. Various functional blocks are explained in the following sections.

A. Microcontroller

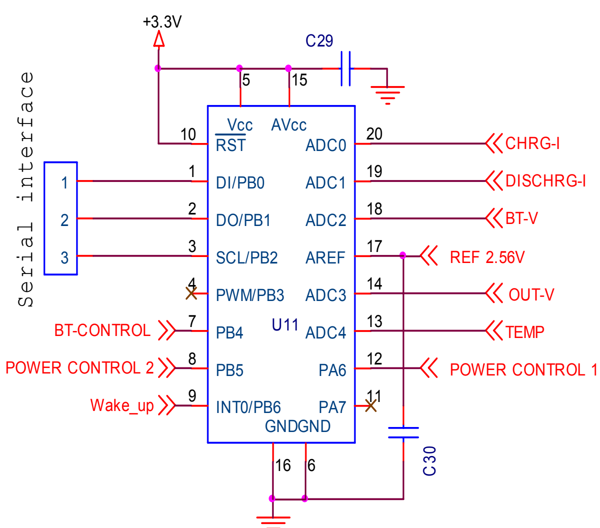

Figure 8: Schematic of microcontroller circuit

The hardware is designed around ATtiny26L an 8–bit microcontroller. The microcontroller makes analog measurements, generates necessary control signals for switching the regulators of temperature and current measurement circuits and supervises the complete process of battery gas gauging (figure 8). The wakeup or interrupt on pin change features enable the microcontroller to be highly responsive to external events, still featuring the lowest power consumption while in the power-down mode.

Serial Interface - The measured parameters can be read by an external device through a 3–wire USI provided. The serial interface not only facilitates reading of the parameters, but also allows them to be written, to tune the design for a custom application. The clock for serial synchronous communication is provided by the external device, which facilitates the transfer to be carried out at any baud rate.

B. Wakeup Circuit

A Schmitt trigger is used to design a free running oscillator with a time period of 1000 ms (figure 9). The oscillator output, a square wave with 50% duty cycle, is fed to an edge detector circuit which generates a pulse of 250 µs for every 1000 ms. This pulse forms a wakeup interrupt signal. The microcontroller on recognizing the interrupt comes out of the power down mode, generates control signal for switching ON the power regulators and goes back to power down mode.

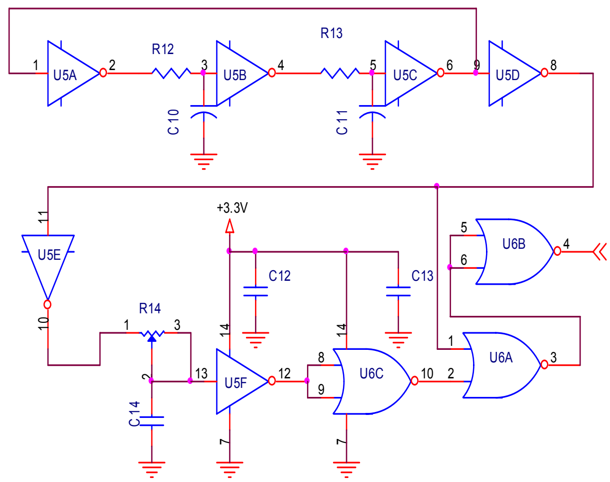

Figure 9: Schematic of wakeup circuit

C. *Temperature Measurement*

The temperature measurement circuit measures the battery temperature in the range -40 °C to +90 °C and converts the temperature into a voltage level 0 to 2.5 V (figure 10). The voltage level 0, 1.25V and 2.5V corresponds to -40 °C, 25 °C and +90 °C battery temperature respectively. The temperature of the battery pack is measured using a precision temperature sensor LM335. The sensor provides an output voltage proportional to the battery temperature. The voltage reference is buffered using an OpAmp. Both the reference and the temperature sensor output form the two inputs of the differential amplifier. The amplifier OP290 having a gain of 1.923 provides an output of 1.25 V at 25°C.

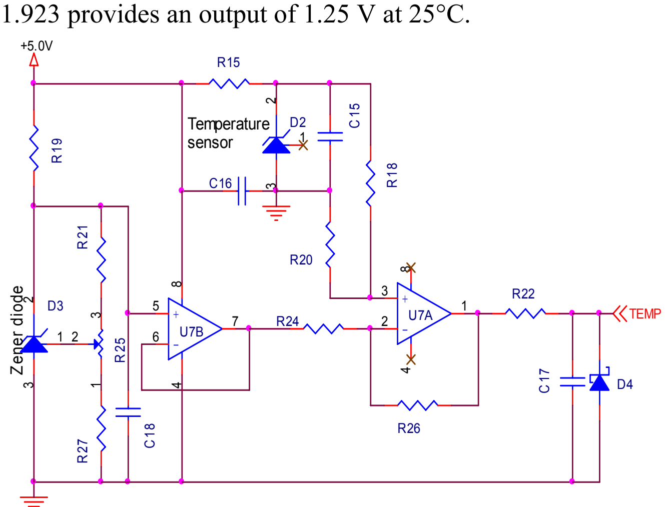

Figure 10: Schematic of temperature detector circuit

D. *Battery Voltage, Load Voltage and Current Sensing*

The basic function of this block is to generate signals for the measurement of battery voltage and battery current.

- The battery voltage from 0 V – 20 V is converted into a range 0 to 2.5 V, with 2.5 V representing 20 V.
- The load voltage from 0 V – 20 V is converted into a range 0 to 2.5 V. With 2.5 V representing 20 V.

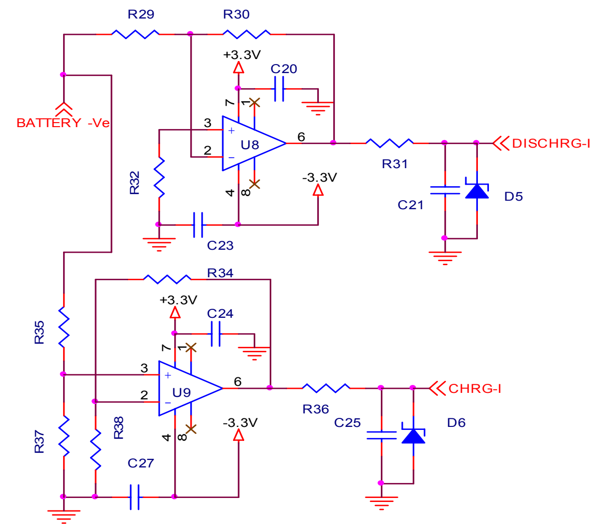

Figure 11: Schematic of current measurement circuit

- The battery charging current in the range 0 to 5 Amps is measured and is converted into a voltage range 0 to 2.5 V, with 2.5 V representing 5 Amp charging current. A precision current sensing resistor (0.02 Ω) is placed in the charging path. Thus a voltage 100 mV is developed corresponding to a charging current of 5Amp. This is amplified using a precision OpAmp OP97 (figure 11). The amplifier has a gain of 25 thus producing a voltage of 2.5 V at 5Amp.
- The battery discharging current in the range 0 to 10 A is measured and is converted into a voltage range 0 to 2.5 V, with 2.5 V representing 10 Amp discharging current. The amplifier OP97 has a gain of 12.5 thus producing a voltage of 2.5 V at 10 A.

E. *Power Supply Unit*

Details of the various power sources are given below.

- *Power source for temperature measurement circuit* – The temperature measuring circuit operates on a single supply of +5V DC. A micro power voltage regulator MAX663 is used here to generate +5V. Figure 12.

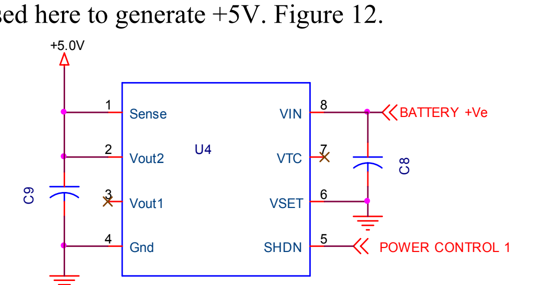

Figure 12: Schematic of power regulator design for temperature measurement circuit

- *Power source for current measurement circuit* – The current measuring circuit operates on dual supply of +3.3V DC and -3.3V DC. Micro power voltage regulator MAX663 generates +3.3V and a CMOS voltage converter ICL7660 generate -3.3V DC (figure 13). The reference voltage for the ADC (2.56V, generated by a low power zener), required by the microcontroller is also powered by this source.

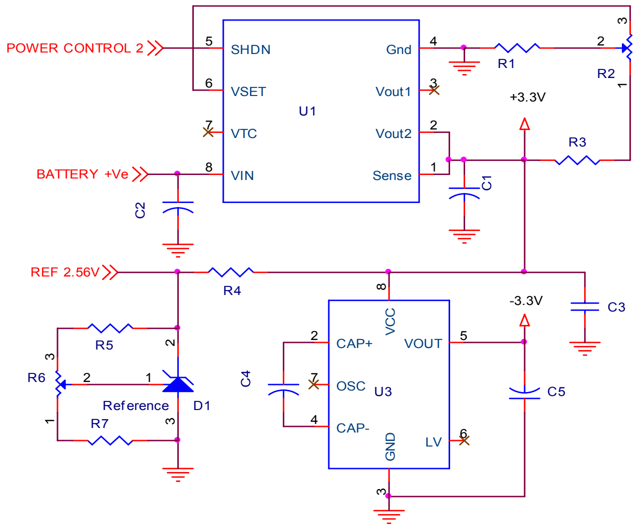

Figure 13: Schematic of power regulator design for the current measurement circuit

- *Power source for the controller and wakeup timer* – Micro power voltage regulator MAX663 is used to generate +3.3V DC and needs to be powered all the time, as the wakeup circuit is active all the time.

IV. Experimental Results

Summary of Results

The proposed design described in section (II) and section (III) was implemented and rigorously tested. Figure 14 shows the final implementation of the proposed gas gauging circuit. The design validation confirmed prediction of the reserved battery charge with an accuracy of 5%.

Measurements on current required by each circuit during power down and during active mode were recorded and the results are summarized in Table 1. It is noted that the wake up circuit and its regulator are always in active mode and the power consumed by this circuit is 22.94 µA. Similarly the battery and load voltage measurement circuit are also always active while they only draw 10.08 µA current. The measurements were taken for battery voltage equal to 13.2 V.

The microcontroller when in power down mode draws about 1 µA current as compared to 700 µA in the active mode. The total time for which the microcontroller is active is 1.5 ms and the period for which it is in power down mode is 998.5 ms. An ON/OFF ratio of 1:665 is achieved. The average current of the microcontroller is reduced from 700 µA to 2.04 µA and power reduction by a factor of 343.18 is achieved.

The current measurement circuit and temperature measurement circuits are usually OFF; the regulators associated with these circuits are in shut down mode. The circuits are switched ON for 5.8 ms once every 1000 ms for taking measurements. The average current of temperature circuit is reduced from 560.35 µA to 3.25 µA with power reduction by a factor of 172.42. Similarly the average current of current measurement circuit is reduced from 1890 µA to 10.96 µA and power reduction by a factor of 172.45 is achieved. It is noted that the average current drawn by the circuit is 55.69 µA as against 3302.79 µA if switching of circuits is not implemented.

Table 1: Details of current drawn by different functional blocks

Sr.	Description of the Circuit	Average Current	
1.	**Wakeup Circuit and Master Processor**		22.94 µA
	Regulator +3.3V	9.90 µA	
	Oscillator Circuit and Edge detector	11.00 µA	
	Master Processor	2.04 µA	
2.	**Temperature Measurement Circuit**		7.15 µA
	Regulator + 5.0V	3.90 µA	
	Temperature circuit - 2.3315V Reference, Temperature Sensor, and Amplifier circuit	3.25 µA	
3.	**Current Measurement Circuit**		15.52 µA
	Regulator + 3.3V, -3.3V and 2.56V Reference	4.56 µA	
	Current Amplifier circuit	10.96 µA	
4.	**Battery and Load Voltage Measurement**		10.08 µA
	Battery Voltage Measurement	5.04 µA	
	Load Voltage Measurement	5.04 µA	
	Total Average Current Drawn		55.69 µA

V. Conclusions

This paper has presented a novel approach to the battery gas gauging and detailed the design of a micro power state of charge monitor using commercially available ICs. The efforts have been tailored to address the hardware and software design aspects so as to reduce the overall power requirement in the measuring circuit. This is well supported by presenting the hardware design of various functional blocks (section III).

The first objective of the proposed design was to efficiently exploit the power down and sleep mode features available in the new micro power devices. The devices selected in the implementation of hardware design supports this. The implementation is based on: Keeping the microcontroller in power down mode, to wake up for making measurements, processing, control or display of data. This is achieved by designing a micro power free running oscillator that generates an interrupt of 250 µs every 1000 ms for the microcontroller; And switching ON the current and temperature measurement circuits only for talking measurements by the microcontroller.

The second objective of the proposed design was to reduce the total power requirement of the gas gauging circuit so that it is less than 60 µA. We have noted that without compromising the accuracy of measurements an average current requirement of 55.69 µA is achieved. This is 12.84% in 1 year for a battery of 3800 mAH capacity

The third objective of the design was to accurately predict the battery reserve time in minutes and the reserved battery charge, by applying necessary corrections to the measured charge and an accuracy of 5% is reported in the design.

The experimental observations illustrated in section IV confirm the utility of the proposed design. The critical timing signals arrived at, as described in section II, is an effort of extraneous testing of each hardware module. Measurements on each of the functional blocks have confirmed the complete functionality of the proposed design. The hardware and software design was tested on a prototype 2 layer PCB. The design is implemented using DIL packages and leaded components to verify the design objectives.

In future it is planned to implement the design using SMD devices so as to reduce the overall size of the PCB. Further, the design can be improved for operation in a dynamically changing environment, where changes in temperature and discharge currents are encountered frequently.

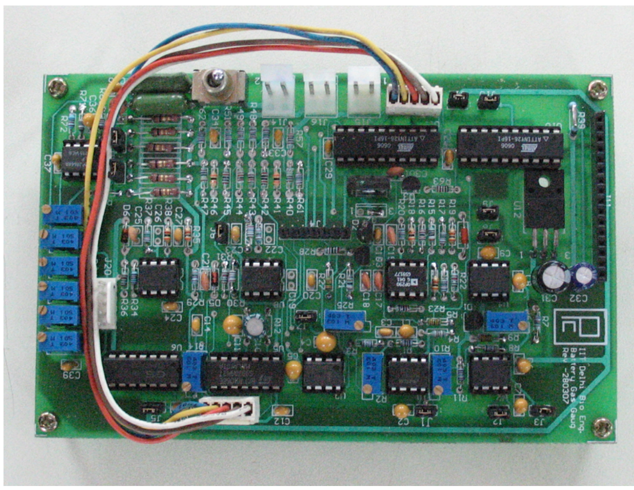

Figure 14: The snapshot of the proposed micro power state-of-charge battery monitor implementation

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