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HCS08 microcontroller based novel PWM controller for battery charger application

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***Abstract*--This paper describes the design of microcontroller based battery charger to charge NiCd battery with charging method, balancing technique and battery protection. Depending on the battery charge state, which is determined by Freescale HCS08 microcontroller the charging process is modified. Fast charging does not have negative effects on the effective capacity of the battery and on battery cycle-life. This paper proposes the microcontroller based battery charger circuit, which is more efficient in terms performance, safety of battery and cost.**

Index Terms— **Battery Charger, microcontroller, HCS08, PWM, Buck Convertor.**

I. INTRODUCTION

At the core of a battery charger is the DC–DC converter that acts as a regulated power source. The charger hardware is capable of regulating the charger output in a number of modes, such as constant voltage, constant current or constant voltage with a current limit. The charger is a control system in itself. The type and capacity of the battery determines the mode of operation of the battery controller— namely, a constant current source or a constant voltage source. The voltage and current set points are also determined by the type and capacity of the battery. The parameters, current and voltage, are controlled using the PWM technique. In the PWM technique, the frequency of the signal is maintained constant, and the width of the pulse or the duty cycle of the signal is varied. This variation is reflected as a change in voltage and/or current at the output. The switching regulator reads the parameters through a feedback circuit, and the battery controller operates based on the control algorithm. The PWM output is obtained by comparing the actual value of the parameter under control with the corresponding set point. In the constant voltage mode, the converter voltage is compared with the voltage set point. In contrast, in the constant current mode, the voltage developed by the charging current across a sense resistor is compared with the current set point.

Determining battery state is the first stage to minimize charging time without negative effects on battery life. Constant voltage and constant current charging are usual ways to charge batteries. The constant voltage charging approach employs an equivalent series resistance to control power flow to charge the battery and keep the battery voltage constant. The constant current charging approach keeps the charging current constant until the battery voltage reaches a designated value.

The use of microcontrollers in battery chargers implies several advantages, as the battery intrinsic characteristics, the number of series-connected units and the load curve of the battery can be defined in the internal memory of the processor via software. Thus the charging process provides more controllable results, becoming reliable and preserving the battery life. An additional control loop can even be implemented in order to monitor the battery temperature, since the excessive heating in the fast-charging process may damage the battery. [1]

This paper proposes a Low cost microcontroller-based battery charger circuit that employs Freescale HCS08QG8 microcontroller to control the charging process. The NiCd and NiMH batteries are charged using the constant current method with battery protection.

II. BATTERY AND ITS CHARGING

The most commonly used batteries in the market are the Ni-Cd, Ni-NH and Li-ion types, all of which have their capacity measured in mAh. This value indicates the amount of current the battery can supply for a certain amount of time. For example a 500 mAh battery should be able to supply 500mA continuously for 1 hour or 50mA for 10 hours. Simply speaking, the larger the battery capacity, measured in mAh, the longer the battery can supply current.

In order to achieve maximum efficiency and cost-effectiveness from the battery it is essential to ensure that the battery is fully charged. To do this it is not only necessary to choose battery chargers that can recharge batteries in a short time but also to detect when the battery is in the fully charged state. For the purpose of a quick-charge in one hour, the current of the charger must stay at 500mAh/1h=500mA. For a so-called 500mAh capacity battery, a charging current of 500mA is called 1C. If Ni-Cd or Ni-NH batteries are recharged without first fully discharging, then they will suffer from a reduction in their overall capacity, a phenomenon known as the memory effect. During the recharge process it is important to know when the battery has reached the fully charged condition. Without the ability to detect this condition, the charger will continue to source current into the battery even after it has reached the fully charged state, a situation which can cause damage to batteries. The following shows the method to detect the fully charged state of Ni-Cd, Ni-NH batteries [2].

Terms and definitions:

VBAT: Battery voltage, measured by taking the presently measured value and averaging it with the previous three measurements.
VMAX: highest safest battery voltage
VPEAK: maximum value of VBAT
ΔV: VPEAK - VBAT

The charging methods for both Ni-Cd and Ni-NH batteries are the same. The following describes several methods of detecting when the full charge condition has been reached:

1. By measuring ΔV: In a fully charged condition the battery voltage will fall. If successive reductions of 10mV is detected 8 times (ΔV > 10mV for 8 times), the battery will be taken as being in a fully charged state.
2. By measuring VPEAK: If VBAT is found to be less than VPEAK after a time period of one minute then the battery can be considered fully charged, however if VBAT is greater than or equal to VPEAK after one minute the timer should be reset and the value measured again after a similar period of time.
3. By measuring VMAX: When VBAT reaches VMAX, the battery can be considered fully charged.
4. By using a safe timing method: if the charging time is greater than the setup time, the battery can be considered fully charged.
5. By measuring battery temperature: when the battery is in the fully charged condition the temperature will rise if charging continues, providing a fully charged measurement parameter.[2].

Fast charging of Ni-Cd, Ni-NH batteries can only be done after the battery voltage has exceeded 2.5V. Until this point is reached the battery has to be charged at a current of 0.1C, after the battery voltage has exceeded 2.5V then a fast charge current of 1C can be applied. In battery charger design it is also necessary to include a function to automatically detect if a battery has been placed in the charger. To achieve this, the charger should from time to time check the voltage on the battery holder; if this voltage exceeds 0.3V then it could be assumed that a battery has been placed in the charger, if the voltage is less than 0.3V then it could be assumed no battery has been placed in the charger. When detected, the placed battery should be placed in a standby condition ready for charging. Because of the limitation of only being able to charge one set of batteries at a time, the standby batteries need to be charged individually. If, after charging, the battery is not removed from the charger it will remain in the standby condition. To fully prevent it being charged again it must be removed from the charger. As for discharging before charging, Ni-Cd and Ni-NH batteries need to be discharged with a current of 0.1C. When the voltage falls to below 2.2V, the charger will stop discharging the battery and begin the charging cycle automatically.

If the measured voltage on the rechargeable battery is lower than 0.3V, the charging process will not be executed. When the voltage exceeds 0.3V, the charger will charge the battery with a constant current of 0.1C until the voltage reaches 2.5V at which point the charging current will be increased to 1C. Depending upon the charger, whenever the VPEAK status or ΔV occurs, the charging process will end.

Charging curve for Ni-Cd and Ni-NH batteries is shown in figure 1.

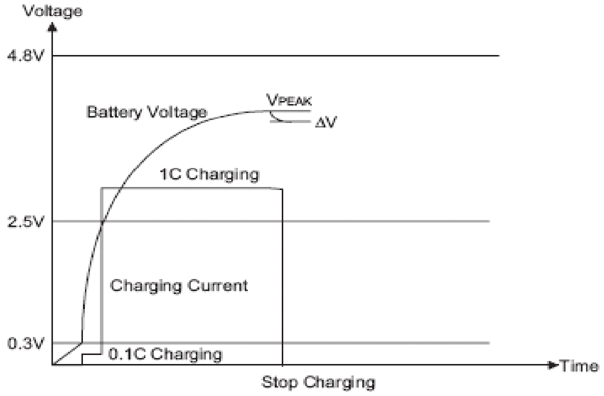

Fig.1 Charging Curve for Ni-Cd /Ni-MH batteries

1. If the voltage of a rechargeable battery exceeds VMAX, (VMAX=4.8V), this will be detected as an over voltage error condition and the charger will cease operation. Possible reasons for this may be a wrongly inserted battery.
2. If the charging time exceeds 80 minutes, this indicates a battery of larger capacity which will require a longer charging time. Other reasons for longer charging times may be a battery in poor condition, in which case the charger may be unable to detect a VPEAK status or ΔV condition and therefore continue charging. A default charging time of 80 minutes will also provide a safety precaution against overcharging and possible damage to the battery or other dangerous conditions.

III. CONTROL ALGORITHM

The PWM output is obtained by comparing the actual value of the parameter under control with the corresponding set point. In the constant voltage mode, the converter voltage is compared with the voltage set point. In contrast, in the constant current mode, the voltage developed by the charging current across a sense resistor is compared with the current set point. Controllers are differentiated based on the method of regulation of parameters in accordance with the corresponding set points.

In a proportional controller, the actual value and the set value are compared, and the resulting error value is used. The drawback of a proportional controller is the possibility of a steady state error. Adding an integral component to the control algorithm eliminates this error. [6].

The equation for a proportional plus integral (PI) controller is:

$$u(t)= \left(k1 \times e(t) + k2 \times \int e(t)dt\right) \qquad (1)$$

To be useful for a microcontroller-based (discrete) system, the integral is approximated by a running sum of the error signal. Therefore, an equation in the differential form is expressed as follows:

$$U[k] = \left(C1 \times e[k] + C2 \times \sum_{j=0}^{k-1} e[j] \right) \qquad (2)$$

Where, C1 and C2 are constants. Equation 2 is the position algorithm. A better representation of Equation 2 is described in Equation 3, as follows:

$$U[k-1] = \left| C1 \times e[k-1] + C2 \times \sum_{j=0}^{k-2} e[j] \right| \qquad (3)$$

Subtracting Equation 3 with Equation 2 and rearranging the terms yields:

$$U[k] - U[k-1] = (Kp \times e[k] + Ki \times e[k-1]) \qquad (4)$$

where, *Kp* and *Ki* are the proportional and integral constants, respectively. Equation 4 is the velocity algorithm, and is a convenient expression as only the incremental change in the manipulated variable is calculated. The charging algorithms are designed based on the type of battery and the current state of charge for that battery. [5]

IV. CHARGING PROCESS AND ICROCONTROLLER

The Freescale MC9S08QG8 is a member of the low-cost, high-performance HCS08 Family of 8-bit microcontroller units. It consists of 20-MHz HCS08 CPU and rich set of peripherals like: ADC - 8-channel, 10-bit analog-to-digital converter, ACMP - Analog comparator module with option to compare to internal reference; output can be optionally routed to TPM module. SCI -Serial communications interface module; SPI — Serial peripheral interface module ; IIC — Inter-integrated circuit bus module; TPM- 2-channel timer/pulse-width modulator; each channel can be used for input capture, output compare, buffered edge-aligned PWM, or buffered center-aligned PWM; KBI — 8-pin keyboard interrupt module with software selectable polarity on edge or edge/level modes. The block diagram of microcontroller is shown in figure 2. [5]

The battery charger application uses Port B of HCS08QG8 as ADC inputs. Timer 0 is used in PWM mode and the output is tapped at the Timer 0 output pin. The system clock is derived from the internal precision oscillator of the HCS08. The reference voltage required for the ADC is generated internally by the HCS08, hence the external component requirement and the Bill of Material cost is reduced. The step-down DC–DC (buck) converter provides a voltage or current appropriate to the NiMH battery. The buck converter modulates a higher voltage (from the external source) with a varying pulse width (PWM method) to generate a lower voltage. The pulse width is controlled by the control algorithm based on the values obtained from The feedback section consists of four differential amplifiers/attenuators. The parameters controlled by the first three amplifiers are the converter voltage (VOUT), the battery voltage (VBATT), and the battery current (IBATT). The battery current and the converter current are same.

The Block diagram of battery charger unit is shown in figure3.

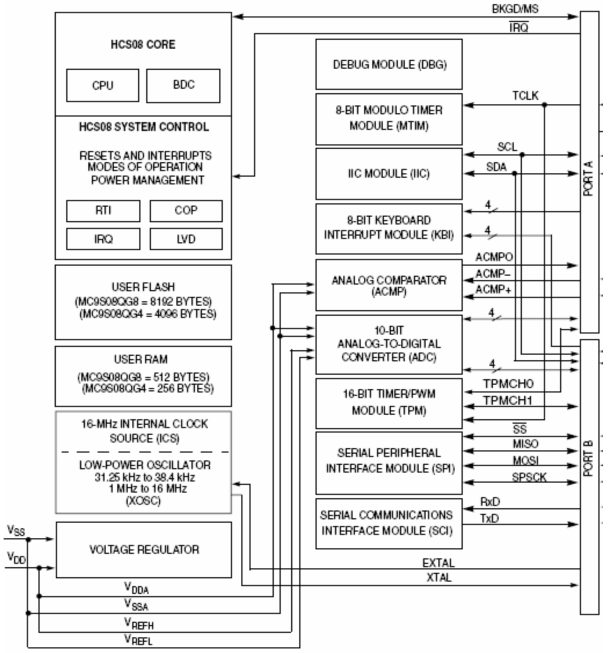

Fig. 2 Block Diagram of Freescale MC9208QG8 Microcontroller

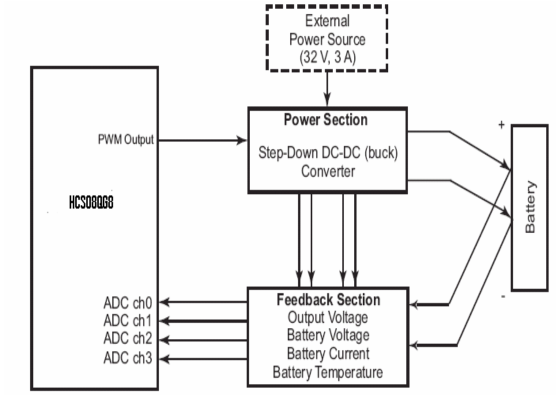

Fig.3 Block Diagram of Battery Charger Unit

V. SOFTWARE IMPLEMENTATION

The safety and termination thresholds are calculated based on the battery parameters. The set points for the DC-DC step-down (buck) converter voltage, the current, and the current limit are calculated. After these one-time calculations are complete, the charger software enters into an infinite loop, which is broken only by a successful charge completion or a safety error. Inside the infinite loop, the ADC reads the actual values for the converter output voltage, the battery voltage, the current, and the temperature (temperature is measured only if the battery features a temperature sensor). The ADC measures the output voltage and the output current of the DC–DC converter as feedback to the controller. The ADC also measures the voltage at the battery terminals as an input to determine the charge termination. Measurement of the output voltage, the output current, and the battery voltage are the basic measurements. The current across the battery terminals is same as the measured converter output current. For batteries featuring built-in temperature sensors, the charger reads the battery temperature in addition to the basic measurements. The temperature measurement is significant from the safety point of view.

After the actual values (VOUT, VBATT, and IBATT) are determined, they are checked for safety limit compliance. The safety routine is responsible for the overall safety features associated with the battery charger. The charger ensures safety by comparing the actual converter voltage, the battery voltage, and the battery temperature with the calculated thresholds. Crossing these thresholds switches off the PWM output, which turns off the converter output and terminates charging functions. Such termination protects the batteries in the case of a device failure.

If all the actual values are within limits, the battery is tested for full charge. For NiMH batteries, the battery is considered to be completely charged if the battery voltage stops increasing (zero Δ V termination). If the battery is not completely charged, the duty cycle required for maintaining the set points at the converter output is calculated by the control algorithm.

The control algorithm implements proportional plus integral (PI) control to derive the PWM output. The timer ISR is invoked every five milliseconds. The PWM value computed by the control algorithm is loaded into the PWM generators to be transmitted via the output pin. The 16-bit timer PWM mode offers a programmable switching frequency based on the reload value. This flexibility allows designers to trade off between accuracy and frequency of the PWM switching signal. A lower frequency results in a higher reload value and a higher resolution in the pulse width variation. The timer ISR updates the charge termination variables every 10 s.

VI. DC-DC BUCK CONVERTER

Step-down (buck) switching converters are integral to modern electronics. They can convert a voltage source (typically 8 V to 25 V) into a lower regulated voltage (typically 0.5 V to 5 V). Step-down converters transfer small packets of energy using a switch, a diode, an inductor and several capacitors. Though substantially larger and noisier than their linear-regulator counterparts, buck converters offer higher efficiency in most cases. This section covers only step-down regulator topology – one with a PWM switching frequency and operation in the continuous-current mode (CCM). To highlight the intricacies of step-down converter design, a detailed analysis for calculating the various component values. Four design parameters are required: input-voltage range, regulated output voltage, maximum output current and the converter's switching frequency. Fig.4 lists these parameters, along with the circuit illustration and basic components required for a buck converter. [3]

Inductor Selection: Calculating the inductor value is most critical in designing a step-down switching converter. First, assume the converter is in CCM, which is usually the case. CCM implies that the inductor does not fully discharge during the switch-off time. The following equations assume an ideal switch (zero on resistance, infinite off-resistance and zero switching time) and an ideal diode:

$$L = (V_{IN_{MAX}} - V_{OUT}) \times \frac{V_{OUT}}{V_{IN_{MAX}}} \times \frac{1}{f_{SW}} \times \frac{1}{LIR \times I_{OUT_{MAX}}} \qquad (5)$$

where f_{SW} is the buck-converter switching frequency and LIR is the inductor-current ratio expressed as a percentage of IOUT (e.g., for a 300-mA p-p ripple current with a 1-A output, LIR = 0.3 A/1 A = 0.3 LIR). An LIR of 0.3 represents a good tradeoff between efficiency and load-transient response. Increasing the LIR constant - allowing more inductor ripple current -quickens the load-transient response, and decreasing the LIR constant - thereby reducing the inductor ripple current - slows the load-transient response. Peak current through the inductor determines the inductor's required saturation-current rating, which in turn dictates the approximate size of the inductor. Saturating the inductor core decreases the converter efficiency, while increasing the temperatures of the inductor, the MOSFET and the diode. You can calculate the inductor's peak operating current as follows:

$$I_{PEAK} = I_{OUT_{MAX}} + \frac{\Delta I_{INDUCTOR}}{2}, where$$

$$\Delta I_{INDUCTOR} = LIR \times I_{OUT_{MAX}} = (V_{IN_{MAX}} - V_{OUT}) \times \frac{V_{OUT}}{V_{IN_{MAX}}} \times \frac{1}{F_{SW}} \times \frac{1}{L}$$

Output Capacitor Selection: Output capacitance is required to minimize the voltage overshoot and ripple present at the output of a step-down converter. Large overshoots are caused by insufficient output capacitance, and large voltage ripple is caused by insufficient capacitance as well as a high equivalent-series resistance (ESR) in the output capacitor. The maximum allowed output-voltage overshoot and ripple are usually specified at the time of design. Thus, to meet the ripple specification for a step-down converter circuit, you must include an output capacitor with ample capacitance and low ESR.

The problem of overshoot, in which the output-voltage overshoots its regulated value when a full load is suddenly removed from the output, requires that the output capacitor be large enough to prevent stored inductor energy from launching the output above the specified maximum output voltage. Output-voltage overshoot can be calculated using the following equation:

$$\Delta V = \left(\sqrt{V_{OUT}^{2} \frac{L(I_{OUT_{MAX}} + \frac{\Delta I_{INDUCTOR}}{2}}{C_0}} \right) - V_{OUT} \qquad (6)$$

Rearranging Eq. 2 yields:

$$C_0 = \frac{L\left(I_{OUT_{MAX}} + \frac{\Delta I_{INDUCTOR}}{2} \right)^2}{\left(\Delta V + V_{OUT} \right)^2 - V_{OUT}^2}, \qquad (7)$$

where CO equals output capacitance and ΔV equals maximum output-voltage overshoot.

Output ripple due to the capacitance alone is given by:

$$V_{OUT_{CAPACITOR}} = \frac{1}{2C_0} \times \frac{V_{IN_{MAX}} - V_{OUT}}{L} \times \left(\frac{V_{OUT}}{V_{IN_{MAX}}} \times \frac{1}{f_{SW}} \right)^2$$

ESR of the output capacitor dominates the output voltage ripple. The amount can be calculated as follows:

$$V_{OUT_{ESR}} = I_{L_{RIPPLE}} \times EST_{C_0} = \Delta I_{INDUCTOR} \times ESR_{C_0}$$

Be aware that choosing a capacitor with very low ESR may cause the power converter to be unstable.

Adding the output-voltage ripple due to capacitance value (the first term in Eq. 8) and the output-capacitor ESR (the second term in Eq. 8) yields the total output-voltage ripple for the step-down converter:

$$V_{OUT_{RIPPLE}} = \frac{1}{2C_0} \times \frac{V_{IN_{MAX}} - V_{OUT}}{L} \times \left(\frac{V_{OUT}}{V_{IN_{MAX}}} \times \frac{1}{f_{SW}} \right)^2 + \Delta I_{INDUCTOR} \times EST_{C_0} \qquad (8)$$

Input Capacitor Selection: The input capacitor's ripple-current rating dictates its value and physical size, and the following equation calculates the amount of ripple current the input capacitor must be able to handle:

$$I_{C_{1_{RMS}}} = I_{OUT_{MAX}} \frac{\sqrt{V_{OUT}\,(V_{IN} - V_{OUT})}}{V_{IN}}$$

The input capacitance required for a step-down converter depends on the impedance of the input power source. For common laboratory power supplies, 10 µF to 22 µF of capacitance per ampere of output current is usually sufficient.

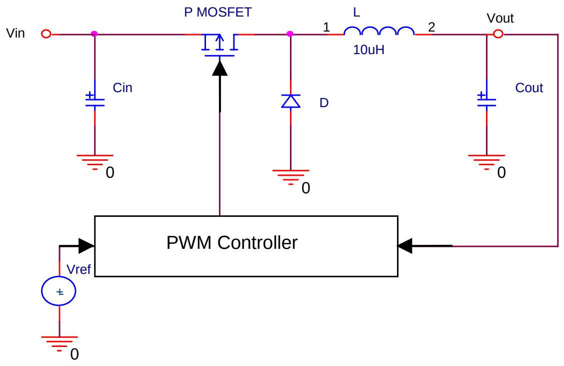

Fig. 4. Basic step-down Converter Circuit with operating parameters.

Diode Selection: Power dissipation is the limiting factor when choosing a diode. The worst-case average power can be calculated as follows:

$$P_{DIODE} = \left(1 - \frac{V_{OUT}}{V_{IN_{MAX}}} \right) \times I_{OUT_{MAX}} \times V_D , \qquad (9)$$

where V_D is the voltage drop across the diode at the given output current $I_{out_{max}}$. (Typical values are 0.7 V for a silicon diode and 0.3 V for a Schottky diode.) Ensure that the selected diode will be able to dissipate that much power. For reliable operation over the input-voltage range, one must also ensure that the reverse-repetitive maximum voltage is greater than the maximum input voltage ($V_{RRM} \geq V_{IN_{MAX}}$). The diode's forward-current specification must meet or exceed the maximum output current (i.e. $I_{F_{AV}} \geq I_{OUT_{MAX}}$).

MOSFET Selection: MOSFET is selected purely on the basis of PWM frequency required, the rated current. Power rating can be also criteria, as switching losses constitute a smaller portion of the MOSFET's power dissipation.

VII. CONCLUSION

This paper has proposed a novel microprocessor-based battery charger circuit that monitors the charging process preserving the battery lifetime. It employs HCS08 which demonstrates that the use of programmable ICs consists in a versatile solution since the battery characteristics, the load curve of the battery, can be defined in the internal memory via an algorithm.

VIII. REFERENCES

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