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APPLICATION NOTE

Simple Switchmode Lead-Acid Battery Charger

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Abstract

Lead-acid batteries are finding considerable use as both primary and backup power sources. For complete battery utilization, the charger circuit must charge the battery to full capacity, while minimizing over-charging for extended battery life. Since battery capacity varies with temperature, the charger must vary the amount of charge with temperature to realize maximum capacity and life. Simple, low cost circuits are currently available for small, low power requirements, while more complex solutions are affordable only on larger more expensive systems. Often the greatest challenge is in designing mid-size, mid-price systems, where obtaining optimum performance at moderate cost and complexity may be nearly impossible without dedicated integrated circuits. This paper describes a compact lead-acid battery charger, which achieves high efficiency at low cost by utilizing switchmode power circuitry, and provides high charging accuracy by employing a dedicated control IC. The circuit described can be easily adapted to lower or higher power applications.

Lead-Acid Basics

Lead-acid battery chargers typically have two tasks to accomplish. The first is to restore capacity, often as quickly as practical. The second is to maintain capacity by compensating for self discharge. In both instances optimum operation requires accurate sensing of battery voltage and temperature.

When a typical lead-acid cell is charged, lead sulfate is converted to lead on the battery's negative plate and lead dioxide on the positive plate. Over-charge reactions begin when the majority of lead sulfate has been converted, typically resulting in the generation of hydrogen and oxygen gas. At moderate charge rates most of the hydrogen and oxygen will recombine in sealed batteries. In unsealed batteries however, dehydration will occur.

The onset of over-charge can be detected by monitoring battery voltage. Figure 1 shows battery voltage verses percent of previous discharge capacity returned at various charge rates. Over charge reactions are indicated by the sharp rise in cell voltage. The point at which over-charge reactions begin is dependent on charge rate, and as charge rate is increased, the percentage of returned capacity at the onset of over-charge diminishes. For over-charge to coincide with 100% return of capacity, the charge rate must typically be less than C/1 (1/100 amps of its amp-hour capacity). At high charge rates, controlled over-charging is typically
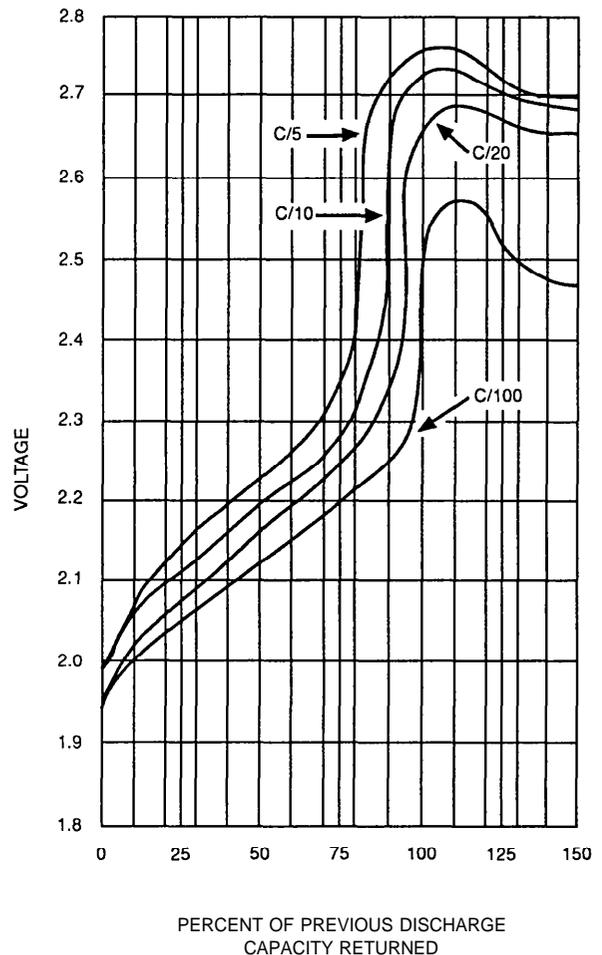

PERCENT OF PREVIOUS DISCHARGE
CAPACITY RETURNED

Figure 1. Over-charge reactions begin earlier (indicated by the sharp rise in cell voltage) when charge rate is increased. (Reprinted with the permission of Gates Energy Products, Inc.,)

employed with sealed batteries to return full capacity as quickly as possible.

To maintain capacity on a fully charged battery, a constant voltage is applied. The voltage must be high enough to compensate for self discharge, yet not too high as to cause excessive over-charging. While simply maintaining a fixed output voltage is a relatively simple function, the battery's temperature coefficient of -3.9mV/degree C per cell adds complication. If battery temperature is not compensated for, loss of capacity will occur below the nominal design temperature, and over-charging with degradation in life will occur at elevated temperature.

Charging Algorithm

To satisfy the aforementioned requirements and thus provide maximum battery capacity and life, a charging algorithm which breaks the charging cycle down into four states is employed. The charging algorithm is illustrated by the charger state diagram shown in figure 2. Assuming a fully discharged battery, the charger sequences through the states as follows:

1. Trickle-charge If the battery voltage is below a predetermined threshold, indicative of a very deep discharge or one or more shorted cells, a small trickle current is applied to bring the battery voltage up to a level corresponding to near zero capacity (typically 1.7V/cell@ 25 degrees C). Trickle charging at low battery voltages prevents the charger from delivering high currents into a short as well as reducing excessive out-gassing when a shorted cell is present. Note that as battery voltage increases, detection of a shorted cell becomes more difficult.

2. Bulk-charge Once the trickle-charge threshold is exceeded the charger transitions into the bulk-charge state. During this time full current is delivered to the battery and the majority of its capacity is restored.

3. Over-charge Controlled over charging follows bulk-charging to restore full capacity in a minimum amount of time. The over-charge voltage is dependent on the bulk-charge rate as illustrated by figure 1. Note that on unsealed batteries minimal over-charging should be
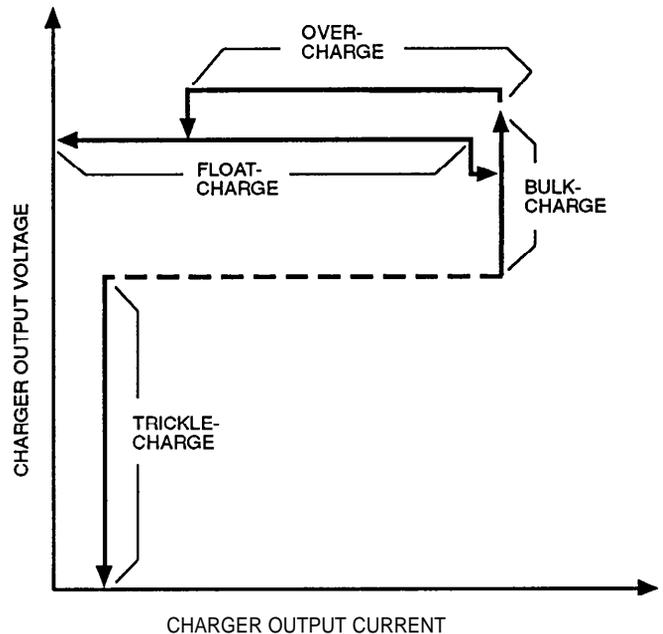

Figure 2. The charging algorithm is broken down into four states

employed to minimize out-gassing and subsequent dehydration. Initially overcharge current is the same as bulk-charge current. As the over-charge voltage is approached, the charge current diminishes. Over-charge is terminated when the current reduces to a low value, typically one-tenth the bulk charge rate.

4. Float-Charge To maintain full capacity a fixed voltage is applied to the battery. The charger will deliver whatever current is necessary to sustain the float voltage and compensate for leakage current. When a load is applied to the battery, the charger will supply the majority of the current up to the bulk-charge current level. It will remain in the float state until the battery voltage drops to 90% of the float voltage, at which point operation will revert to the bulk charge state.

Charger Circuit Design

There are many possible circuit configurations which will provide the necessary control and output charging current. For efficient operation, particularly at higher output currents, switching power circuitry is preferred. To minimize cost as well as complexity each IC used must provide as much functionality as possible. A circuit topology was chosen which utilizes two special purpose ICs and a general purpose op-amp to provide all of the control

functions, while a discrete MOSFET output stage handles the power. The circuit design is modular to simplify modification for different application requirements.

The charger circuit can be divided into three basic blocks. The first is the voltage loop control and state control logic which executes the control algorithm while providing temperature compensation. The second is the switchmode controller which regulates the current to the battery as commanded by the voltage loop control and state control logic. The third is the output power stage which is sized to efficiently deliver the charging current.

Voltage Loop Control and State Control Logic

Initially designed for charging small lead-acid batteries using a linear pass transistor for current control, the UC3906 directly implements the voltage loop control and state control logic while providing the appropriate temperature compensation. The block diagram of the UC3906 is shown in figure 3.

Battery voltage is monitored with a resistor divider string. This network establishes the float voltage, the over-charge voltage, and the trickle-charge threshold voltage by comparing to the precision temperature compensated reference. Since temperature is monitored on chip it is critical that the battery and the UC3906 are in close proximity, and
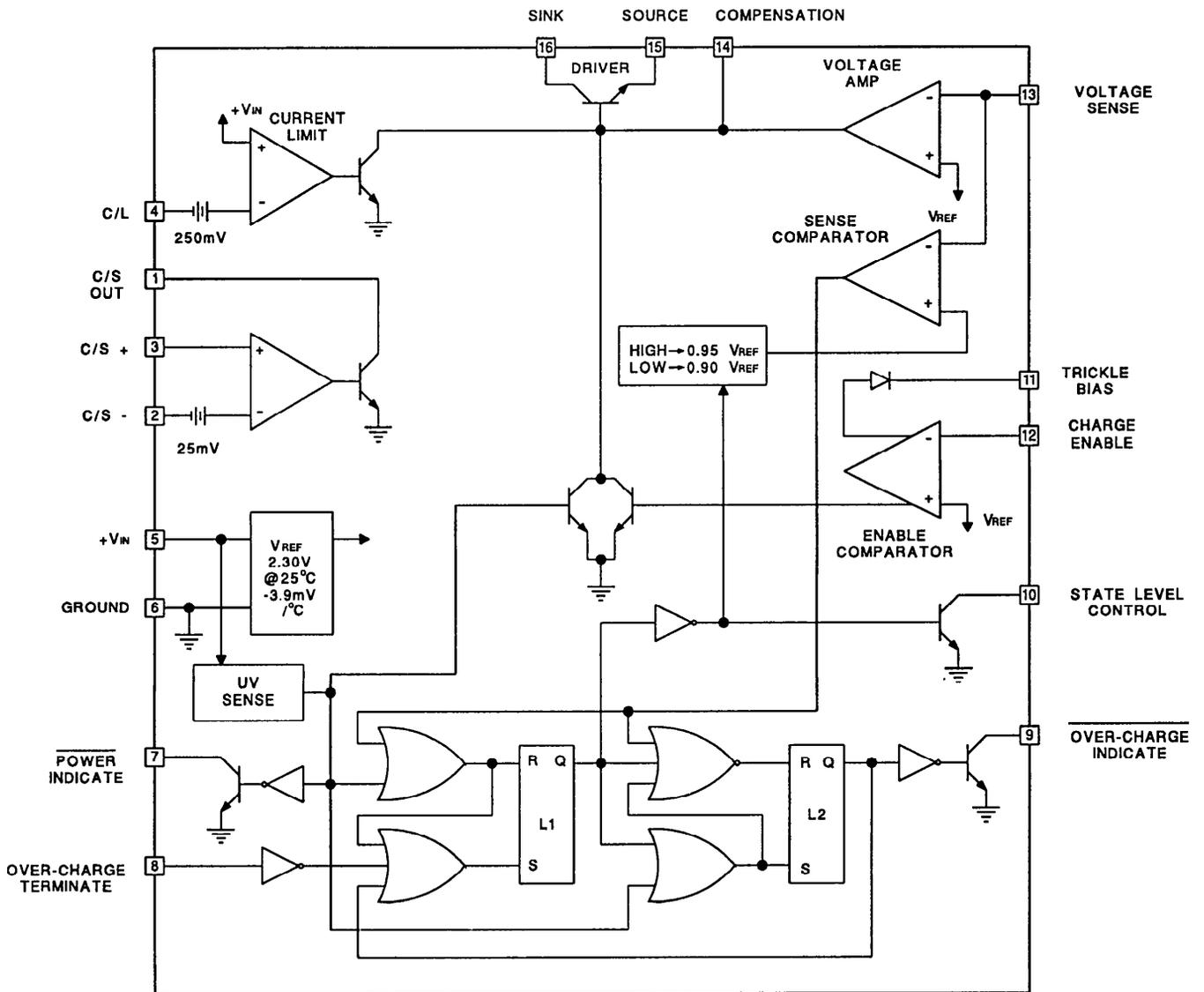

Figure 3. UC3906 Lead-Acid Battery Charger block diagram

that self-heating or heating from other components is minimized.

The differential current sense comparator is used to terminate over-charging and transition to the float state. The voltage amplifier provides gain and compensation for the voltage loop. The UC3906 is covered in detail in reference [3].

Switchmode Current Source

The charging algorithm places great demands on the current loop. during bulk charge full current must be supplied, yet during the float state the current draw may be only a few milliamps. This equates to a dynamic range in excess of 60 dB which can be very difficult to achieve with common peak current mode techniques. The wide dynamic range also requires operation with both continuous and discontinuous inductor current, potentially adding complication to voltage loop stabilization. Although load resistors can be employed to reduce the required dynamic range, their use can significantly degrade efficiency, particularly while in the float state. Note that a high value load resistor (10 k) is employed to assure operation down to zero output current and to provide a discharge path for the output capacitor. Additionally, to provide precise bulk and trickle-charge current levels the closed current loop transconductance must be accurate. Average current feedback will circumvent these potential problems, and is the key to a successful implementation of the switching current source for this application.

Figure 4 shows the basic implementation of average current feedback. While slightly more complicated than typical peak current mode control schemes, average current feedback offers several critical performance enhancements. The high gain of the error amplifier at lower frequencies provides high closed current loop accuracy and accommodates the large output stage nonlinearity which occurs when the inductor current becomes discontinuous. Good switching spike noise immunity is inherent with this technique permitting stable operation at narrow duty cycles.

A UC3823 PWM controller shown in figure 5 was chosen for the current loop control circuit for several reasons. First and most importantly it is capable of operating linearly from very small duty cycles to near
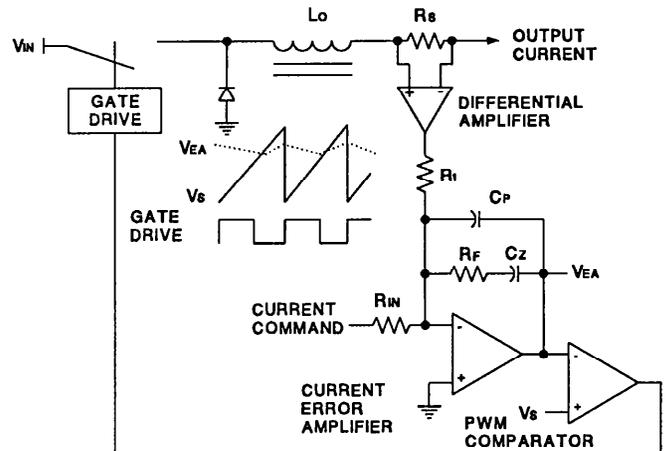

Figure 4. Average Current Feedback Loop

100% duty cycle. Secondly the error amplifier bandwidth and configuration are well suited to the average current loop's requirements. Additionally, the output driver affords a simple interface to most discrete output power stages.

A separate op-amp configured as a differential amplifier senses the output current and level shifts the signal to the appropriate voltage. The offset and common mode rejection of this amplifier are the major source of current loop error.

Output Power Stage

To simplify development a simple buck regulator output stage was used. For further simplicity the high-side switch is implemented using a direct coupled P-channel MOSFET. A switched current sink provides gate charge, turning the MOSFET on while a zener diode limits the gate to source voltage to 12 volts. A second emitter switched current sink drives a PNP which removes gate charge, turning the MOSFET off. Undoubtedly this output stage is suitable for many applications, although higher power capability and efficiency can be achieved using N-channel devices. A relatively low value output inductor was chosen to minimize size and cost since operation in the discontinuous current mode is of no concern with average current feedback. Output ripple voltage is also not critical so the output capacitor was selected for ripple current capability. High frequency ringing caused by circuit parasitics is damped with a small RC snubber across the catch rectifier. A rectifier in series with the output
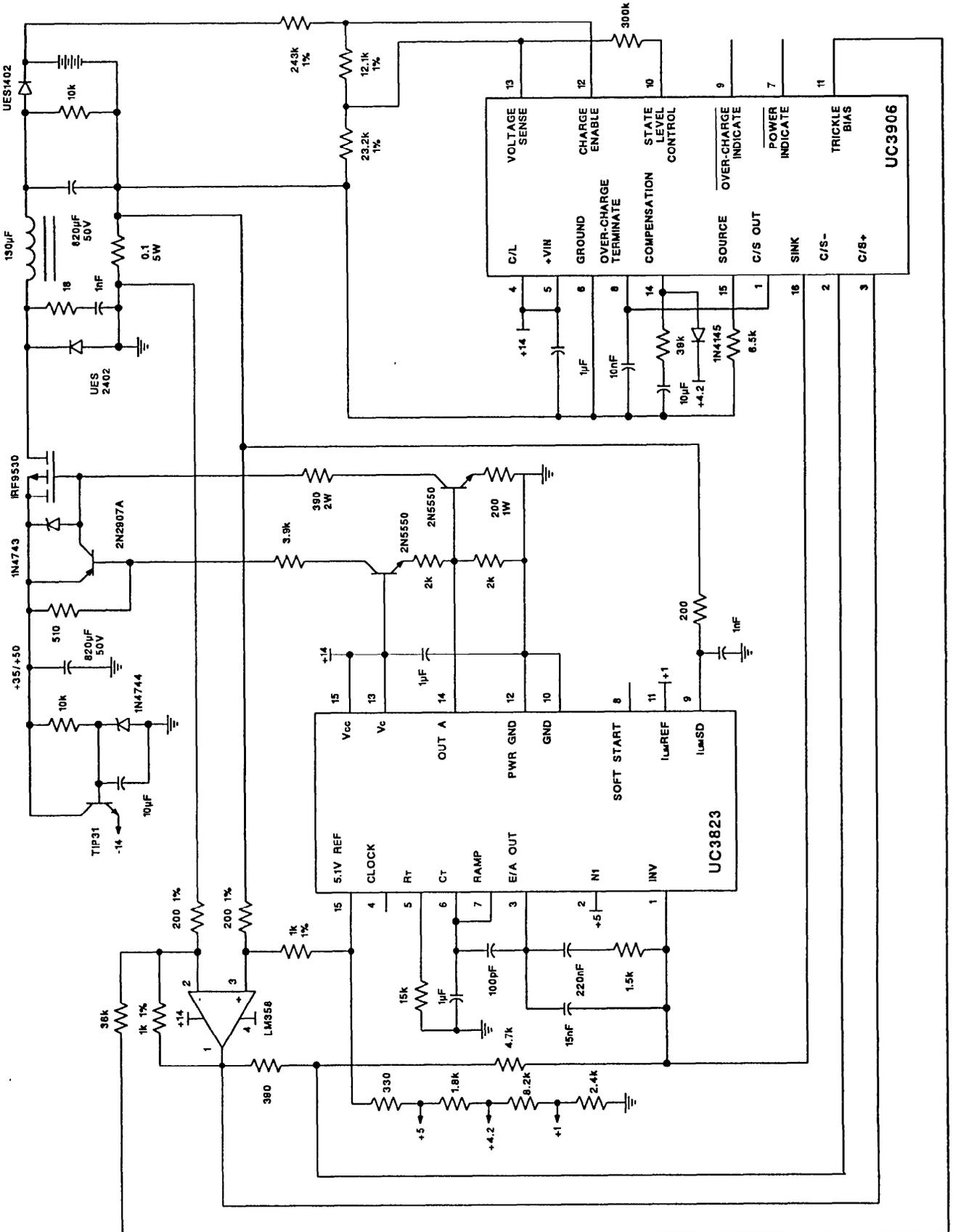
Figure 5. UC3823 High speed PWM Controller Block Diagram

prevents the battery from back driving the charger when input power is disconnected.

Complete Charger Circuit

A complete schematic for the switch-mode charger is shown in figure 6. Control circuit power is supplied from an emitter follower off a zener shunt regulator. The PWM frequency is set to 100 kHz as a reasonable compromise between output filter component size and switching loss. Output current is sensed in the battery return lead to minimize common mode voltage errors. This arrangement also allows direct current sensing for pulse by pulse current limiting adding further protection during abnormal conditions. The differential amplifier is set to a gain of 5 with the output signal referenced to the UC3823s 5.1 V reference.

The current feedback signal is summed with the current command signal at the error amplifier's inverting input. To accommodate worst case offset in both the error amplifier and the differential amplifier and allow zero output current, the non-inverting input of the error amplifier is biased 130 mV below the 5.1 V reference. Trickle bias is accomplished by injecting a small current into the differential amplifier's negative op-amp input, thus causing a proportional output current to balance the loop. Additionally, a 100 pF capacitor across the PWM comparator inputs enhances noise immunity, particularly at low duty cycles.

For maximum control and float voltage accuracy, the UC3906s ground is connected to the battery's negative terminal, thereby rejecting the current sense resistors voltage drop. The internal emitter follower output transistor interfaces to the current source as illustrated in figure 7. The voltage amplifier drives the output current command signal. The current command signal is limited by clamping the voltage amplifier output through a diode to 4.2 V. The clamp also prevents the emitter follower from

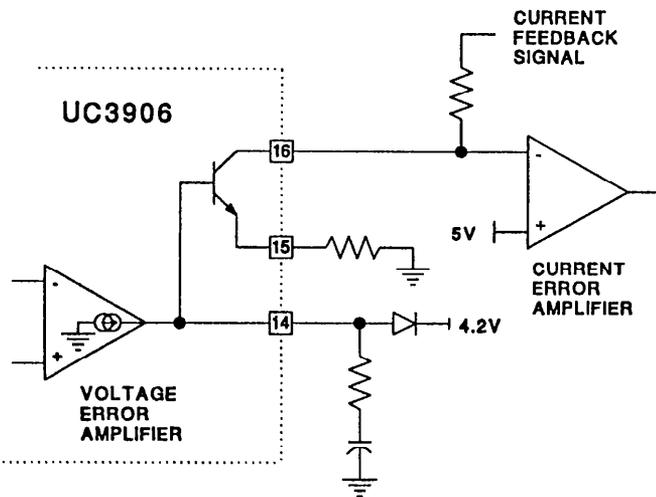**Figure 6.** Switchmode Lead-Acid Battery charger schematic

Figure 7. The UC3906's output transistor provides the interface to the switchmode current source.

saturating which would cause a large difference between collector and emitter currents due to excessive base drive.

Battery voltage is sensed by the resistor divider string, with the values shown for a typical **24** V **(12** cell) application. Other battery voltages are easily accommodated by simply changing the divider values using the procedure presented in the UC3906 data sheet, although changes in input voltage may require modification of the output circuit and the control circuit power supply. The resistor divider establishes all of the state transitions with the exception of over-charge terminate, which is determined by detecting when the output current has tapered off to approximately one-tenth the bulk charge level. This is accomplished by the UC3906s current sense comparator which senses the appropriately scaled signal from the differential amplifier output.

Current and Voltage Loop Compensation

The charger circuit implements a two loop control system with the current loop operating inside the voltage loop. During trickle-charge, bulk-charge and the beginning of over-charge the voltage loop is saturated and the current loop is essentially driven from a fixed reference.

With continuous inductor current the control to output gain of the current loop shown in figure 4 exhibits a single pole response from the output inductor. The error amplifier gain at the switching

frequency is set such that the amplified inductor current down-slope is less than the oscillator-ramp up-slope as seen by the PWM comparator. By setting the two slopes equal under worst case conditions (at maximum output voltage) maximum closed loop bandwidth is achieved without subharmonic oscillation.

Placing a zero below the minimum loop crossover frequency significantly boosts low frequency gain while a pole placed above the maximum crossover frequency enhances noise immunity. Note that since loop response is not particularly critical for battery charging, conservative compensation with plenty of phase margin is normally employed.

When inductor current becomes discontinuous, the power circuit gain suddenly drops, requiring large duty cycle changes to significantly effect output current. The single pole characteristic of continuous inductor current with its 90 degree phase lag disappears. The current loop becomes more stable, but less responsive. Fortunately the high gain of the error amplifier easily provides the large duty cycle changes necessary to accommodate changes in output current, thereby maintaining good average current regulation.

The block diagram of the voltage loop is shown in figure 8. With an inner transconductance loop the control to output gain of the voltage loop exhibits a single pole response from the output capacitor and equivalent load resistance. While it may initially appear that a simple fixed gain on the voltage amplifier would provide suitable loop compensation, further examination shows a severe drop in voltage gain at high loads, which would drastically reduce DC accuracy. A zero is placed in the voltage amplifier's transfer function to boost low frequency gain and therefore restore DC accuracy.

The current loop's single pole response above its crossover frequency cancels the output stage zero resulting from the output capacitor's capacitance and ESR. Note again that since wide bandwidth is not required for battery charging, the voltage loop crossover frequency is well below both the current loop's pole and the output capacitor's zero. Low leakage capacitors must be used for the compensation network to maintain high DC gain

since the voltage amplifier is a transconductance type. Loop stabilization is covered extensively in references [1] and [2].

Charger Performance Summary

The charger circuit properly executes the charging algorithm, exhibiting stable operation regardless of battery conditions including an open circuit load. The circuit was tested with 6, 12 and 24 V batteries by modifying only the battery voltage sense divider. As would be expected, circuit efficiency was best at high battery voltage, approaching 85% while bulk-charging a 24 V battery with a 40 V input supply voltage.

An analysis of circuit losses indicates several areas where efficiency could be improved. Any accuracy and offset improvement in the differential amplifier will allow a corresponding decrease in current sense resistor value and hence dissipation, while maintaining the same overall current loop accuracy. Replacing the output blocking rectifier with a Schottky would save a few watts if the Schottky's leakage could be tolerated. Further improvement could be made in that area by using a relay to disconnect the charger when input power is removed. A more conservative inductor design with less resistance would save a little over one watt. As expected, the greatest losses occur in the output switch. A lower on resistance FET and a higher peak current gate drive to reduce switching losses could save more than 5 watts. Incorporating a few of these improvements will easily increase circuit efficiency to greater than 90%.

Alternate Circuit Configurations

While the charger circuit as designed may be suitable for many applications, a few modifications should satisfy the majority of additional requirements. Higher voltage batteries can be charged by designing a higher voltage output stage. N-channel MOSFETs are preferable for cost and efficiency reasons, but are more difficult to drive than P-channels. Fortunately, the remainder of the circuit will require minimal modification.

Some applications may require both the battery and charger to share a common ground and thus prohibit current sensing in the batteries negative return. The differential amplifier can sense current at the inductor output if tighter tolerance resistors to improve CMRR are used. While this simple

modification renders a suitable signal for closing the current loop, another current sense signal referenced to ground must be developed for pulse by pulse current limiting. This signal is most easily derived by using a PNP level shift transistor, connecting the base to the 5.1 V reference and the emitter through a resistor to the differential amplifier output.

At higher battery voltages it may be desirable to float with a current rather than a voltage. Varying self-discharge rates of individual cells in high voltage batteries causes inevitable differences in cell charge levels. By employing a float current and applying a small continuous overcharge, variation of charge between cells is minimized. Precise output at float current levels places great demands on current loop accuracy, and will add unnecessary expense to the current sensing circuitry. A more cost effective alternative is to use a fixed linear current source which should be small and inexpensive considering the very low output current.

Thus far the input supply has not been addressed and is assumed to be from a voltage required elsewhere in the system or from a typical line frequency transformer, rectify bridge and filter capacitor. This may represent more than half the cost of the charger, and is certainly the majority of its size and weight. An obvious alternative is to replace the buck output section with a transformer coupled output, taking advantage of the switching control circuit already present. Buck derived circuits such as forward, half-bridge and full-bridge easily interface with the existing design, however resonant and flyback circuits are also applicable. A small (0.75 W) auxiliary supply will be required to power the control circuitry since the modulator will output zero at times, prohibiting the use of a bootstrap winding commonly used on switching power supplies. This
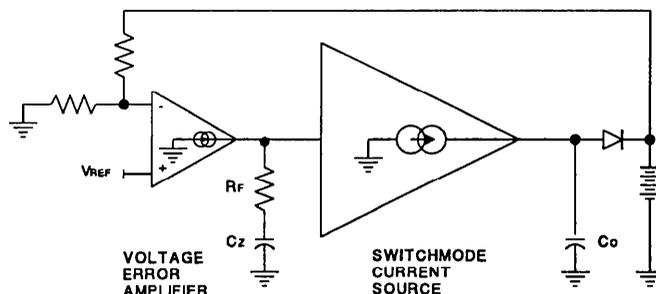

Figure 8. Voltage Control Loop block diagram

approach is particularly cost effective for stand-alone applications, allowing the design of a compact, light weight, high performance charger.

Summary

A practical switchmode lead acid battery charger circuit has been presented which incorporates all of the features necessary to assure long battery life with rapid charging capability. By utilizing special function ICs, component count is minimized, reducing system cost and complexity. With the circuit as presented, or with its many possible variations, designers need no longer compromise charging performance and battery life to achieve a cost effective system.

REFERENCES

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