

IMPROVED CHARGING METHODS FOR LEAD-ACID BATTERIES USING THE UC3906

ABSTRACT

This paper describes the operation and application of the UC3906 Sealed Lead-Acid Battery Charger. This IC provides reductions in the cost and design effort of implementing optimal charge and hold cycles for lead-acid batteries. Described are the design and operation of several charging circuits using this IC. The charger designs use current and voltage sensing combined with sequenced current and voltage control to maximize battery capacity and life for various applications. The presented material provides insight into expected improvements in battery performance with respect to these specific charging methods. Also presented are uses of the many auxiliary functions included on this part. The unique combination of features on this control IC has made it practical to create charge and hold cycles that truly get the most out of a battery.

AN IC FOR CHARGING LEAD-ACID BATTERIES

Battery technology has come a long way in recent years. Driven by the reduction of size and power requirements of processing functions, batteries now are used to provide portability and failsafe protection to a new generation of

electronic systems. Although a number of battery technologies have evolved, the lead-acid cell remains the workhorse of the industry due to its combination of prolonged standby and cycle life with a high energy storage capacity. The makers of uninterruptible power supplies, portable equipment, and any system that requires failsafe protection are taking advantage of the improvements in this technology to provide secondary power sources to their products, for example, the sealed cell, using a trapped or gelled electrolyte, has eliminated the positional sensitivity and greatly reduced the dehydration problem.

The charging methods used to replenish or maintain the charge on a lead-acid battery have a significant effect on the performance of the cells. Building an optimum charger, one that gets the most out of a battery, is not a trivial task. Making sure that a battery undergoes the proper charge and hold cycle requires precision sensing and control of both voltage and current, logic to sequence the charger through its cycle, and temperature corrections — added to the charger's control and sensing circuits — to allow proper charging at any temperature. In the past this has required a significant number of components, and a substantial design effort as well. The UC3906 Sealed Lead-

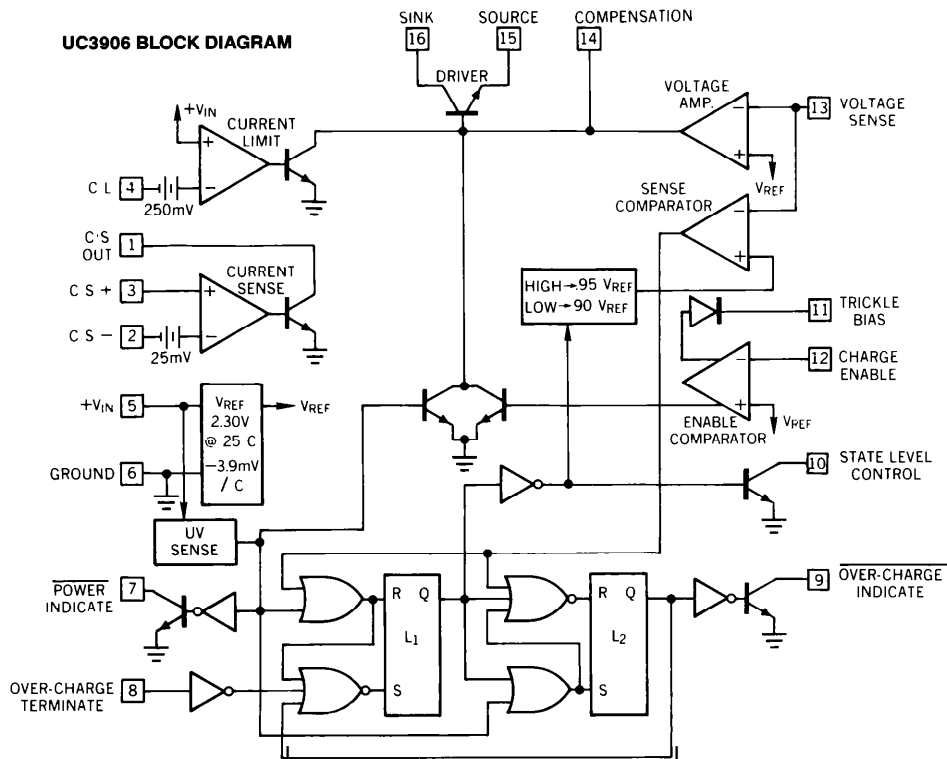


FIGURE 1. The UC3906 Sealed Lead-Acid Battery Charger combines precision voltage and current sensing with voltage and current control to realize optimum battery charge cycles. Internal charge state logic sequences the device through charging cycles. Voltage control and sensing is referenced to an internal voltage that specially tracks the temperature characteristics of lead-acid cells.

Acid Battery Charger has all the control and sensing functions necessary to optimize cell capacity and life in a wide range of battery applications.

The block diagram for the UC3906 is shown in figure 1. Separate voltage loop and current limit amplifiers regulate the output voltage and current levels in the charger by controlling the onboard driver. The driver will supply 25mA of base drive to an external pass element. Voltage and current sense comparators are used to sense the battery condition and respond with logic inputs to the charge state logic. The charge enable comparator on this IC can be used to remotely disable the charger. The comparator's 25mA trickle bias output is active high when the driver is disabled. These features can be combined to implement a low current turn-on mode in a charger, preventing high current charging during abnormal conditions such as a shorted or reversed battery.

A very important feature of the UC3906 is its precision reference. The reference voltage is specially temperature compensated to track the temperature characteristics of lead-acid cells. The IC operates with very low supply current, only 1.7mA, minimizing on-chip dissipation and permitting the accurate sensing of the operating environmental temperature. In addition, the IC includes a supply under-voltage sensing circuit, used to initialize charging cycles at power on. This circuit also drives a logic output to indicate when input power is present. The UC3906 is specified for operation over the commercial temperature range of 0°C to 70°C. For operation over extended temperatures, -40°C to 70°C the UC2906 is available.

WHAT IS IMPORTANT IN A CHARGER?

Capacity and life are critical battery parameters that are strongly affected by charging methods. Capacity, C, refers to the number of ampere-hours that a charged battery is rated to supply at a given discharge rate. A battery's rated capacity is generally used as the unit for expressing charge and discharge current rates, i.e., a 2.5 amp-hour battery charging at 500mA is said to be charging at a C/5 rate. Battery life performance is measured in one of two ways; cycle life or stand-by life. Cycle life refers to the number of charge and discharge cycles that a battery can go through before its capacity is reduced to some threshold level. Standby life, or float life, is simply a measure of how long the battery can be maintained in a fully charged state and be able to provide proper service when called upon. The measure which actually indicates useful life expectancy in a given application will depend on the particulars of the application. In general, both aspects of battery life will be important.

During the charge cycle of a typical lead-acid cell, lead sulfate, $PbSO_4$, is converted to lead on the battery's negative plate and lead dioxide on the battery's positive plate. Once the majority of the lead sulfate has been converted, over-charge reactions begin. The typical result of over-charge is the generation of hydrogen and oxygen gas. In unsealed batteries this results in the immediate loss of water. In sealed cells, at moderate charge rates, the majority of the hydrogen and oxygen recombine before dehydration occurs. In either type of cell, prolonged charging rates significantly above C/500, will result in dehydration, accelerated grid corrosion, and reduced service life.

The onset of the over-charge reaction will depend on the rate of charge. At charge rates of $>C/5$, less than 80% of the cell's previously discharged capacity will be returned as the over-charge reaction begins. For over-charge to coincide with 100% return of capacity, charge rates must typically be reduced to less than C/100. Also, to accept higher rates the battery voltage must be allowed to increase as over-charge is approached. Figure 2 illustrates this phenomenon, showing cell voltage vs. percent return of previously discharged capacity for a variety of charge rates. The over-charge reaction begins at the point where the cell voltage rises sharply, and becomes excessive when the curves level out and start down again.

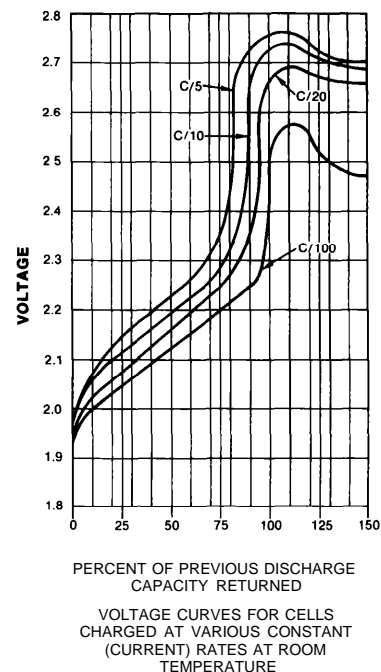


FIGURE 2. Depending on the charge rate, over-charge reactions begin, (indicated by the sharp rise in battery voltage), well below 100% return of capacity. (Reprinted with the permission of Gates Energy Products, Inc.)

Once a battery is fully charged, the best way to maintain the charge is to apply a constant voltage to the battery. This burdens the charging circuit with supplying the correct float charge level; large enough to compensate for self-discharge, and not too large to result in battery degradation from excessive overcharging. With the proper float charge, sealed lead-acid batteries are expected to give standby service for 6 to 10 years. Errors of just five percent in a float charger's characteristics can halve this expected life.

To compound the above concerns, the voltage characteristics of a lead-acid cell have a pronounced negative temperature dependence, approximately $-4.0\text{mV}/^\circ\text{C}$ per 2V cell. In other words, a charger that works perfectly at 25°C may not maintain or provide a full charge at 0°C and conversely may drastically over-charge a battery at $+50^\circ\text{C}$. To function properly at temperature extremes a charger must have some form of compensation to track the battery temperature coefficient.

To provide reasonable re-charge times with a full 100% return of capacity, a charge cycle must adapt to the state of charge and the temperature of the battery. In sealed, or recombinant, cells, following a high current charge to return the bulk of the expended capacity, a controlled over-charge should take place. For unsealed cells the over-charge reaction must be minimized. After the over-charge, or at the onset of over-charge, the charger should convert to a precise float condition.

A DUAL LEVEL FLOAT CHARGER

A state diagram for a sealed lead-acid battery charger that would meet the above requirements is shown in figure 3.

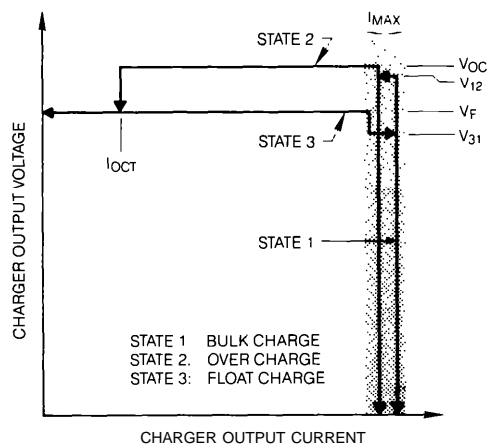


FIGURE 3. The dual level float charger has three charge states. A constant current bulk charge returns 70-90% of capacity to the battery with the remaining capacity returned during an elevated (constant) voltage over-charge. The float charge state maintains a precision voltage across the battery to optimize stand-by life.

This charger, called a dual level float charger, has three states, a high current bulk charge state, an over-charge state, and a float state. A charge cycle begins with the charger in the bulk charge state. In this state the charger acts like a current source providing a constant charge rate at I_{MAX} . The charger monitors the battery voltage and as it reaches a transition threshold, V_{12} , the charger begins its over-charge cycle. During the over-charge, the charger regulates the battery at an elevated voltage, V_{OC} , until the charge rate drops to a specified transition current, I_{OCT} . When the current tapers to I_{OCT} , with the battery at the elevated level, the capacity of the cell should be at nearly 100%. At this point the charger turns into a voltage regulator with a precisely defined output voltage, V_F . The output voltage of the charger in this third state sets the float level for the battery.

With the UC3906, this charge and hold cycle can be implemented with a minimum of external parts and design effort. A complete charger is shown in figure 4. Also shown are the design equations to be used to calculate the element values for a specific application. All of the programming of the voltage and current levels of the charger are determined by the appropriate selection the external resistors R_S , R_A , R_B , R_C .

Operation of this charger is best understood by tracing a charge cycle. The bulk charge state, the beginning, is initiated by either of two conditions. One is the cycling on of the input supply to the charger; the other is a low voltage condition on the battery that occurs while the charger is in the float state. The under-voltage sensing circuit on the UC3906 measures the input supply to the IC. When the input supply drops below about 4.5V the sensing circuit forces the two state logic latches (see figure 1) into the bulk charge condition (L1 reset and L2 set). This circuit also disables the driver output during the under-voltage condition. To enter the bulk charge state while power is on, the charger must first be in the float state (both latches set). The input to the charge state logic coming from the voltage sense comparator reports on the battery voltage. If the battery voltage goes low this input will reset L1 and the bulk charge state will be initiated.

With L1 reset, the state level output is always active low. While this pin is low the divider resistor, R_B is shunted by resistor R_C , raising the regulating level of the voltage loop. If we assume that the battery is in need of charge, the voltage amplifier will be in its stops trying to turn on the driver to force the battery voltage up. In this condition the voltage amplifier output will be over-ridden by the current limit amplifier. The current limit amplifier will control the driver, regulating the output current to a constant level. During this

time the voltage at the internal, non-inverting, input to the voltage sense comparator is equal to 0.95 times the internal reference voltage. As the battery is charged its voltage will rise; when the scaled battery voltage at PIN 13, the inverting input to the sense comparator, reaches $0.95V_{REF}$ the sense comparator output will go low. This will reset the second latch and the over-charge state will be entered. At this time the over-charge indicator output will go low. Other than this there is no externally observable change in the charger. Internally, the starting of the over-charge state arms the set input of the first latch – assuming no reset signal is present – so that when the over-charge terminate input goes high, the charger can enter the float state.

In the over-charge state, the charger will continue to supply the maximum current. As the battery voltage reaches the elevated regulating level, V_{OC} , the voltage amplifier will take command of the driver, regulating the output voltage at a constant level. The voltage at PIN 13 will now be equal to the internal reference voltage. The battery is completing its charge cycle and the charge acceptance will start to taper off.

As configured in figure 4, the current sense comparator continuously monitors the charge rate by sensing the voltage across R_S . The output of the comparator is connected to the over-charge terminate input. Whenever the

charge current is less than I_{OCT} , ($25mV/R_S$), the open collector output of the comparator will be off. When this transition current is reached, as the charge rate tapers in the over-charge state, the off condition of the comparator output will allow an internal $10\mu A$ pull-up current at PIN 8 to pull that point high. A capacitor can be added from ground to this point to provide a delay to the over-charge-terminate function, preventing the charger from prematurely entering the float state if the charging current temporarily drops due to system noise or whatever. When the voltage at PIN 8 reaches its 1V threshold, latch L1 will be set, setting L2 as well, and the charger will be in the float state. At this point the state level output will be off, effectively eliminating R_C from the divider and lowering the regulating level of the voltage loop to V_F .

In the float state the charger will maintain V_F across the battery, supplying currents of zero to I_{MAX} as required. In addition, the setting of L1 switches the voltage sense comparator's reference level from 0.95 to 0.90 times the internal reference. If the battery is now discharged to a voltage level 10% below the float level, the sense comparator output will reset L1 and the charge cycle will begin anew.

The float voltage V_F , as well as V_{OC} and the transition voltages, are proportional to the internal reference on the UC3906. This reference has a temperature coefficient of

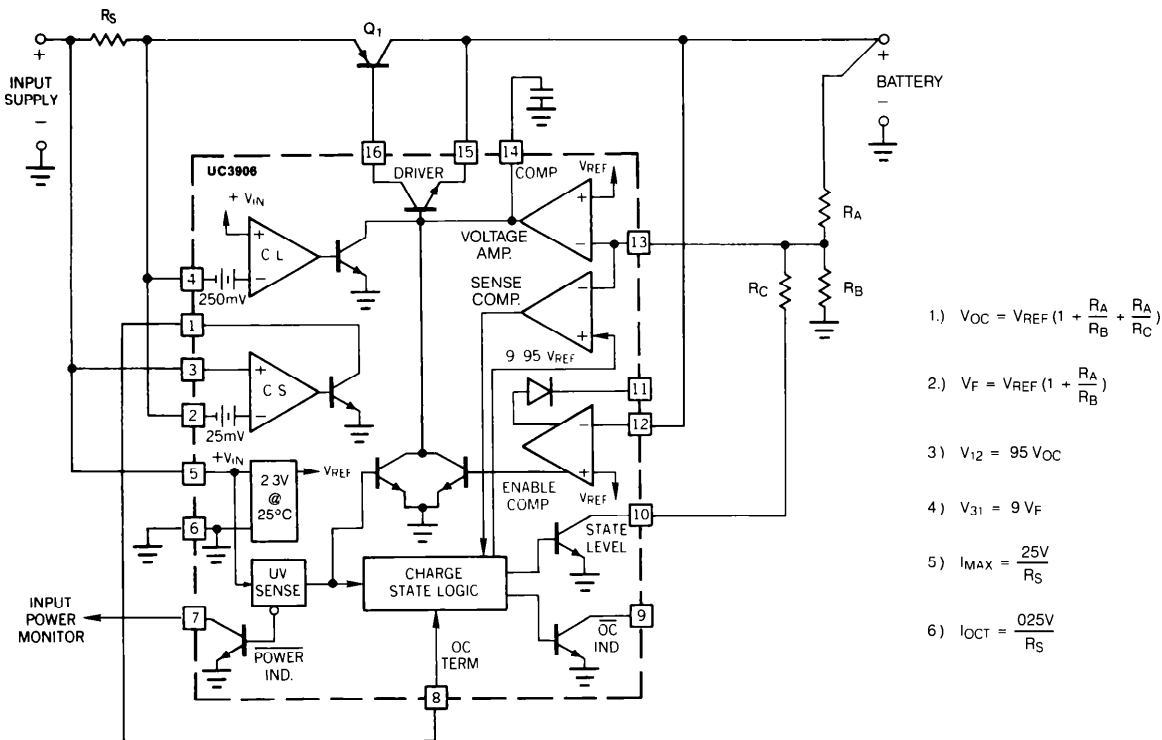


FIGURE 4. Using a few external parts and following simple design equations the UC3906 can be configured as a dual level float charger.

-3.9mV/°C. This temperature dependence matches the recommended compensation of most battery manufacturers. The importance of the control of the charger's voltage levels is reflected in the tight specification of the tolerance of the UC3906's reference and its change with temperature, as shown in figure 5.

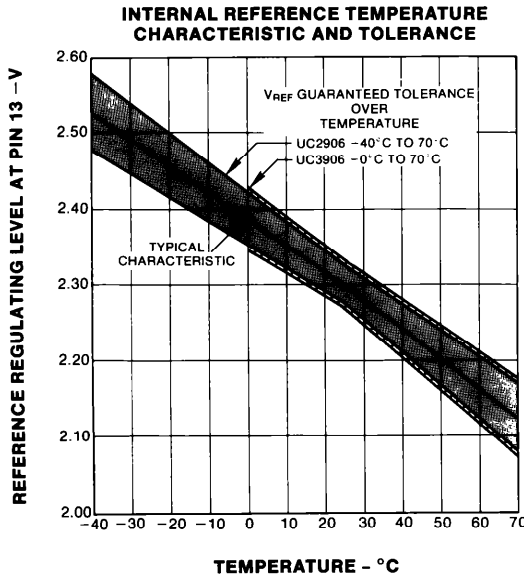


FIGURE 5. The specially temperature compensated reference on the UC3906 is tightly specified over 0 to 70°C (-40 to 70°C for the UC2906), to allow proper charge and hold characteristics at all temperatures.

I_{MAX} , I_{OCT} , V_{OC} , and V_F can all be set independently. I_{MAX} , the bulk charge rate can usually be set as high as the available power source will allow, or the pass device can handle. Battery manufacturers recommend charge rates in the C/20 to C/3 range, although some claim rates up to and beyond 2C are OK if protection against excessive overcharging is included. I_{OCT} , the over-charge terminate threshold, should be chosen to correspond, as close as possible, to 100% recharge. The proper value will depend on the over-charge voltage (V_{OC}) used and on the cell's charge current tapering characteristics at V_{OC} .

I_{MAX} and I_{OCT} are determined by the offset voltages built into the current limit amplifier and current sense comparator respectively, and the resistor(s) used to sense current. The offsets have a fixed ratio of 250mV/25mV. If ratios other than ten are necessary separate current sensing resistors or a current sense network, must be used. The penalty one pays in doing this is increased input-to-output differential requirements on the charger during high current charging. Examples of this are shown in figure 6.

An alternative method for controlling the over-charge state is to use the over-charge indicate output, PIN 9, to initiate an external timer. At the onset of the over-charge cycle the over-charge indicate pin will go low. A timer triggered by this signal could then activate the over-charge terminate input, PIN 8, after a timed over-charge has taken place. This method is particularly attractive in systems with a centralized system controller where the controller can provide the timing function and automatically be aware of the state of charge of the battery.

The float, V_F , and over-charge, V_{OC} , voltages are set by the internal reference and the external resistor network, R_A , R_B , and R_C as shown in figure 4. For the dual level float charger the ranges at 25°C for V_F and V_{OC} are typically 2.3V-2.40V and 2.4V-2.7V, respectively. The float charge level will normally be specified very precisely by the battery manufacturer, little variation exists among most battery suppliers. The over-charge level, V_{OC} , is not as critical and will vary as a function of the charge rate used. The absolute value of the divider resistors can be made large, a divider current of 50µA will sacrifice less than 0.5% in accuracy due to input bias current offsets.

AUXILIARY CAPABILITIES OF THE CHARGER IC

Besides simply charging batteries, the UC3906 can be used to add many related auxiliary functions to the charger that would otherwise have to be added discretely. The enable comparator and its trickle bias output can be used in a number of different ways. The modification of the state diagram in figure 2 to establish a low current turn-on mode

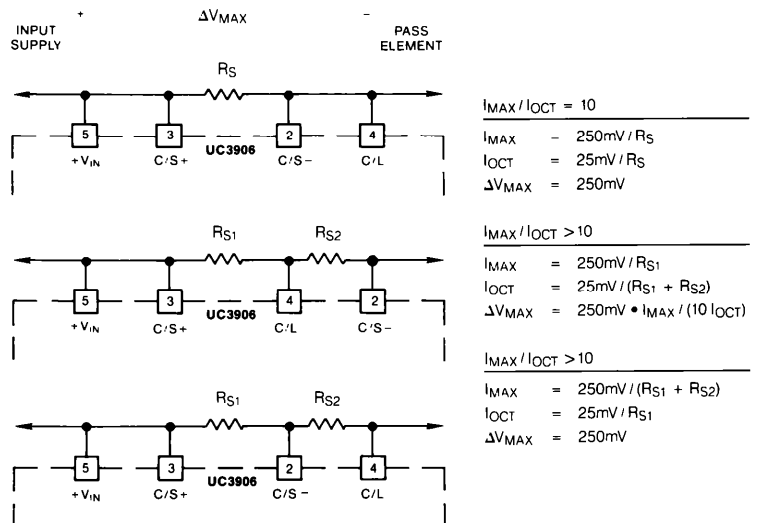


FIGURE 6. Although the ratio of input offset voltages on the current limit and current sense stages is fixed at 10, other ratios for I_{MAX}/I_{OCT} are easily obtained. Note that a penalty for ratios greater than 10 is increased voltage drop across the sensing network at I_{MAX} .

of the charger (see figure 7) is easily done. By reducing the output current of the charger when the battery voltage is below a programmable threshold, the charging system protects against: One, high current charging of a string with a shorted cell that could result in excessive outgassing from the remaining cells in the string. Two, dumping charge into a battery that has been hooked up backwards. Three, excessive power dissipation in the charger's pass element. As shown in figure 7, the enable comparator input taps off the battery sensing divider, When the battery voltage is below the resulting threshold, V_T , the driver on the UC3906 is disabled and the trickle bias output goes high. A resistor, R_T , connected to the battery from this output can then be used to set a trickle current, ($\leq 25\text{mA}$) to the battery to help the charger discriminate between severely discharged cells and damaged, or improperly connected, cells.

In applications where the charger is integral to the system, i.e. always connected to the battery, and the load currents on the battery are very small, it may be necessary to absolutely minimize the load on the battery presented by the charger when input power is removed. There are two simple precautions that, when taken, will remove essentially all reverse current into the charging circuit. In figure 8 the diode in series with the pass element will prevent any reverse current through this path. The sense divider should still be referenced directly to the battery to maintain accurate control of voltage. To eliminate this discharge

path, the divider in the figure is referenced to the open collector power indicate output, PIN 7, instead of ground. Connected in this manner the divider string will be in series with essentially an open when input power is removed. When power is present, the open collector device will be on, holding the divider string end at nearly ground. The saturation voltage of the open collector output is specified to be less than 50mV with a load current of 50 μA .

Figure 9 illustrates the use of the enable comparator and its output to build over-discharge protection into a charger. Over-discharging a lead-acid cell, like over-charging, can severely shorten the service life of the cell. The circuit monitors the discharging of the battery and disconnects all load from the battery when its voltage reaches a specified cutoff point. The load will remain disconnected from the battery until input power is returned and the battery recharged.

This scheme uses a relay between the battery and its load that is controlled by Q1 and the presence of voltage across the load. When primary power is available Q1 is on via D5. The battery is charging, or charged, and the trickle bias output at PIN 11 is off. When input power is removed, C2 provides enough hold-up time at the load to let Q1 turn off, and the relay to close as current flows through R1. The battery is now providing power to the load and, through D1, power to the charger. The charger current draw will typically be less than 2mA. As the battery discharges, the UC3906 will continue to monitor its voltage. When the vol-

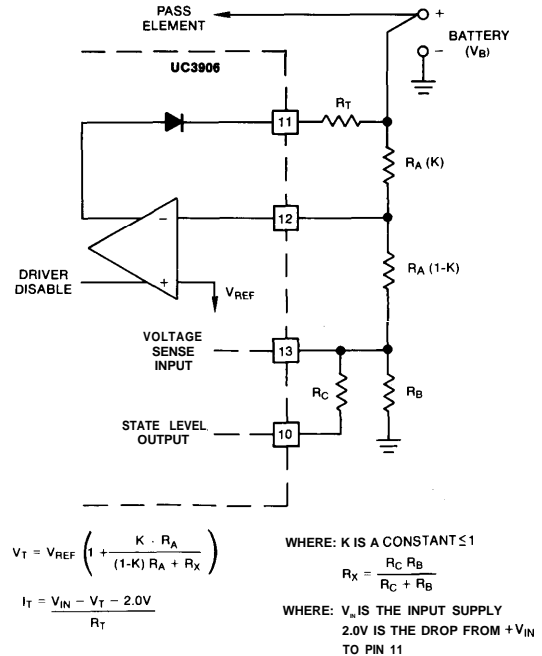
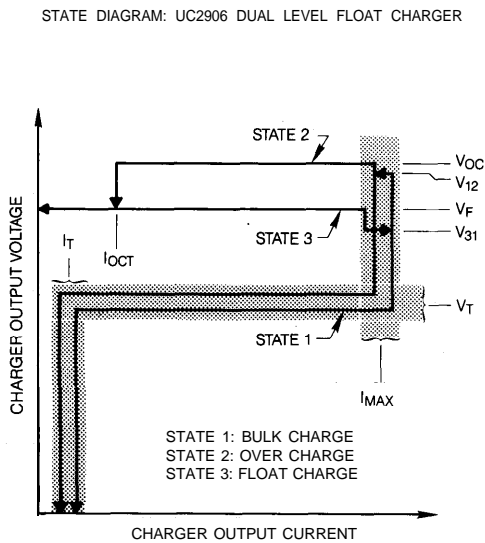


FIGURE 7. The charge enable comparator, with its trickle bias output, can be used to build protection into the charger. The current foldback at low battery voltages prevents high current charging of batteries with shorted cells, or improperly connected batteries, and also protects the pass element from excessive power dissipation.

tage reaches the cut-off level, set by the divider network, R5-R8, the trickle bias output, PIN 11, will go high. Q1 will turn back on and the relay current will collapse opening its contacts. As the load voltage drops, capacitor C1 supplies power to the UC3906 to keep Q1 on. Once the input to the charger has collapsed the power indicate pin, as shown in figure 8, will open the divider string. The battery will remain open-circuited until input power is returned. At that time the battery will begin to recharge.

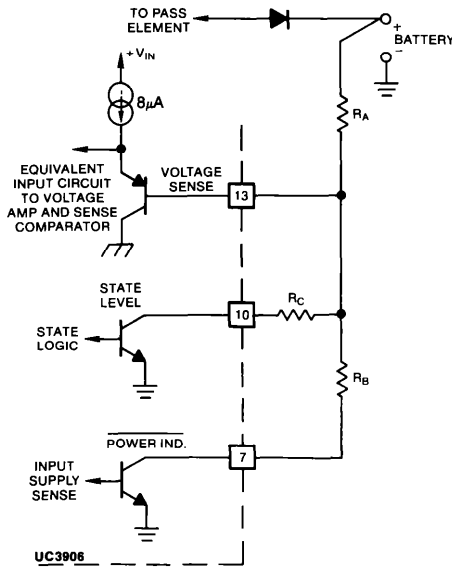


FIGURE 8. By using a diode in series with the pass element, and referencing the divider string to the power indicate pin, pin 7, reverse current into the charger, (when the charger is tied to the battery with no input power), can be eliminated.

CHARGING LARGE SERIES STRINGS OF LEAD-ACID CELLS

When large series strings of batteries are to be charged, a dual step current charger has certain advantages over the float charger of figures 3 and 4. A state diagram and circuit implementation of this type of charger is shown in figure 10. The voltage across a large series string is not as predictable as a common 3 or 6 cell string. In standby service varying self discharge rates can significantly alter the state of charge of individual cells in the string if a constant float voltage is used. The elevated voltage, low current holding state of the dual step current charger maintains full and equal charge on the cells. The holding, or trickle current, IH, will typically be on the order of 0.005C to 0.0005C.

To give adequate and accurate recharge this charger has a bulk charge state with temperature compensated transition thresholds, V12, and V21. Instead of entering an elevated voltage over-charge, upon reaching V12 the charger switches to a constant current holding state. The holding current will maintain the battery voltage at a slightly elevated level but not high enough to cause significant over-charging. If the battery current increases, the charger will attempt to hold the battery at the VF level as shown in the state diagram. This may happen if the battery temperature increases significantly, increasing the self-discharge rate beyond the holding current. Also, immediately following the transition from the bulk to float states, the battery will only be 80% to 90% charged and the battery voltage will drop to the VF level for some period of time until full charging is achieved.

In this charger the current sense comparator is used to regulate the holding current. The level of holding current is determined by the sensing resistor, RSH. The other series

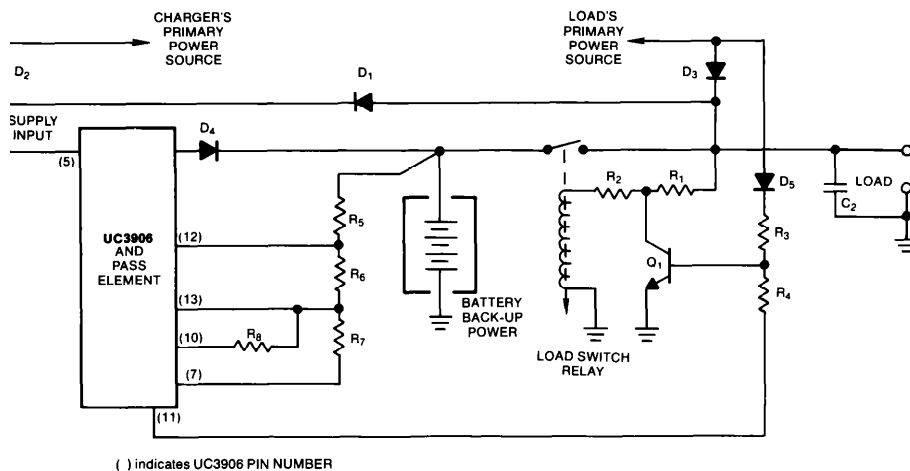


FIGURE 9. Using the enable comparator to monitor the battery voltage a precise discharge cut-off voltage can be set. When the battery reaches the cut-off threshold the trickle bias output switches off the load switch relay and the battery is left open circuited until input power is returned.

resistor, R_E , is necessary for the current sense comparator to regulate the holding current. Its value is selected by dividing the value of I_H into the minimum input to output differential that is expected between the battery and the input supply. If the supply variation is very large, or the holding current large, ($> 25\text{mA}$), then an external buffering element may be required at the output of the current sense comparator.

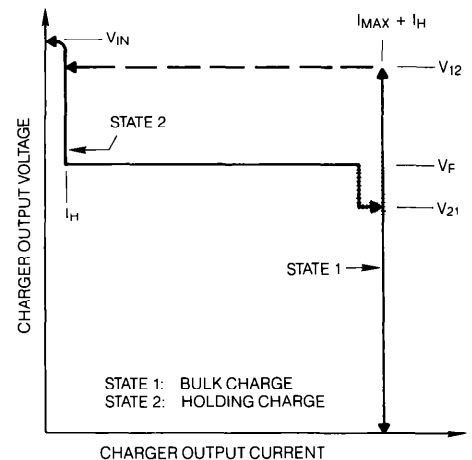
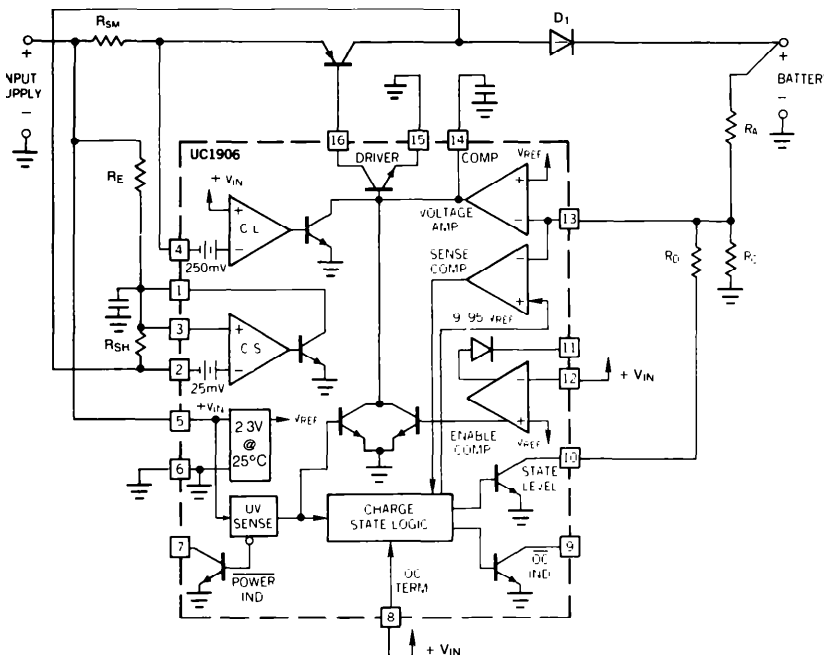
The operating supply voltage into the UC3906 should be kept less than 45V. However, the IC can be adapted to charge a battery string of greater than 45V. To charge a large series string of cells with the dual step current charger the ground pin on the UC3906 can be referenced to a tap point on the battery string as shown in figure 11. Since the charger is regulating current into the batteries, the cells will all receive equal charge. The only offset results from the bias current of the UC3906 and the divider string current adding to the current charging the battery cells below the tap point. R_B can be added to subtract the bulk of this current improving the ability of the charger to control the low level currents. The voltage trip points using this technique will be based on the sum of the cell voltages on the high side of the tap.

PICKING A PASS ELEMENT AND COMPENSATING THE CHARGER

There are four factors to consider when choosing a pass device. These are:

1. The pass device must have sufficient current and power handling capability to accommodate the desired maximum charging rate at the maximum input to output differential.
2. The device must have a high enough current gain at the maximum charge rate to keep the drive current required to less than 25mA.
3. The type of device used, (PNP, NPN, or FET), and its configuration, may be dictated by the minimum input to output differential at which the charger must operate.
4. The open loop gain of both the voltage and the current control loops are dependent on the pass element and its configuration.

Figure 12 contains a number of possible driver configurations with some rough break points on applicable current ranges as well as the resulting minimum input to output differentials. Also included in this figure are equations for the dissipation that results on the UC3906 die, equations for a resistor, R_D , that can be added to minimize this dissipation, and expressions for the open loop gains of both the voltage and current loops.



$$\begin{aligned}
 1.) V_{12} &= .95 V_{REF} \left(1 + \frac{R_A}{R_C} + \frac{R_A}{R_D} \right) & 4.) I_{MAX} &= \frac{.25V}{R_{SM}} \\
 2.) V_F &= V_{REF} \left(1 + \frac{R_A}{R_C} \right) & 5.) I_H &= \frac{.025V}{R_{SH}} \\
 3.) V_{21} &= .9 V_F
 \end{aligned}$$

FIGURE 10. A dual step current charger has some advantages when large series strings must be charged. This type of charger maintains constant current during normal charging that results in equal charge distribution among battery cells.

As reflected in the gain expressions in figure 12, the open loop voltage gains of both the voltage and current control loops are dependent on the impedance, Z_C at the compensation pin. Both loops can be stabilized by adjusting the value of this impedance. Using the expressions given, one can go through a detailed analysis of the loops to predict respective gain and phase margins. In doing so one must not forget to account for all the poles in the open loop expressions. In the common emitter driver examples, 1 and 3, the equivalent load impedance at the output of the charger directly affects loop characteristics. In addition, a pole, or poles, will be added to the loop response due to the roll-off of the pass device's current gain, Beta. This effect will occur at approximately the rated unity gain frequency of the device divided by its low frequency current gain. The transconductance terms for the voltage and current limit amplifiers, (1/1.3K and 1/300 respectively), will start to roll off at about 500KHZ. As a rule of thumb, it is wise to kill the loop gain well below the point that any of these, not-so-predictable poles, enter the picture.

If you prefer not to go through a BODE analysis of the loops to pick a compensation value, and you recognize the fact that battery chargers do not require anything close to optimum dynamic response, then loop stability can be assured by simply oversizing the value of the capacitor used at the compensation pin. In some cases it may be necessary to add a resistor in series with the compensation capacitor to put a zero in the response. Typical values for the compensation capacitor will range from 1000pF to 0.22μF depending on the pass device and its configuration. With composite common emitter configurations, such as example 3 in figure 12, compensation values closer to

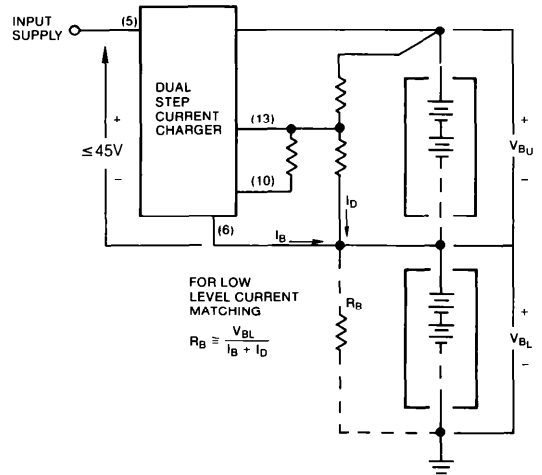


FIGURE 11. A dual step current charger can be configured to operate with input supplies of greater than 45V by using a tap on the battery to reference the UC3906. The charger uses the voltage across the upper portion of the battery to sense charging transition points. To minimize charging current offsets, R_B can be added to cancel the UC3906 bias and divider currents.

the 0.22μF value will be required to roll off the large open loop gain that results from the Beta squared term in the gain expression. Series resistance should be less than 1K, and may range as low as 100 ohms and still be effective.

The power dissipated by the UC3906 requires attention since the thermal resistance, (100°C/Watt) of the DIP package can result in significant differences in temperature between the UC3906 die and the surrounding air, (battery), temperature. Different driver/pass element configurations result in varying amounts of dissipation at the UC3906. The dissipation can be reduced by adding external dropping resistors in series with the UC3906 driver,

	COMMON EMITTER PNP	COMPOSITE FOLLOWER	COMPOSITE COMMON EMITTER	NPN EMITTER FOLLOWER
TOPOLOGY				
UC3906 DRIVER	UC3906 DRIVER	UC3906 DRIVER	UC3906 DRIVER	UC3906 DRIVER
CURRENT RANGE	25mA < I < 1000mA	25mA < I < 1000mA	600mA < I < 15A	25mA < I < 1000mA
MINIMUM ΔV	ΔV > 0.5V	ΔV > 2.0V	ΔV > 1.2V	ΔV > 2.7V
UC3906 DRIVER DISSIPATION	$P_D = \frac{V_{IN} - 0.7V}{\beta_{Q1}} \cdot I - \frac{I^2 R_D}{\beta^2_{Q1}}$	$P_D = \frac{V_{IN} - 0.7V - V_{OUT}}{\beta_{Q1}} \cdot I - \frac{I^2 R_D}{\beta^2_{Q1}}$	$P_D = \frac{V_{IN} - 0.7V}{\beta_{Q1} \beta_{Q2}} \cdot I - \frac{I^2 R_D}{\beta^2_{Q1} \beta^2_{Q2}}$	$P_D = \frac{V_{IN} - 0.7V - V_{OUT}}{\beta_{Q1}} \cdot I - \frac{I^2 R_D}{\beta^2_{Q1}}$
EXPRESSION FOR RD	$R_D = \frac{V_{IN MIN} - 2.0V}{I_{MAX}} \cdot \beta_{Q1 MIN}$	$R_D = \frac{V_{IN MIN} - V_{OUT MAX} - 1.2V}{I_{MAX}} \cdot \beta_{Q1 MIN}$	$R_D = \frac{V_{IN MIN} - 0.7V}{I_{MAX}} \cdot \beta_{Q1 MIN} \beta_{Q2 MIN}$	$R_D = \frac{V_{IN MIN} - V_{OUT MAX} - 1.2V}{I_{MAX}} \cdot \beta_{Q1 MIN}$
OPEN LOOP* GAIN OF THE VOLTAGE CONTROL LOOP	$A_{OV} = \frac{Z_C}{1.3K} \cdot \frac{1}{R_D + 12} \cdot \beta_{Q1} \cdot Z_O \cdot \frac{V_{REF}}{V_{OUT}}$	$A_{OV} = \frac{Z_C}{1.3K} \cdot \frac{V_{REF}}{V_{OUT}}$	$A_{OV} = \frac{Z_C}{1.3K} \cdot \frac{1}{R_D + 12} \cdot \beta_{Q1} \cdot \beta_{Q2} \cdot Z_O \cdot \frac{V_{REF}}{V_{OUT}}$	$A_{OV} = \frac{Z_C}{1.3K} \cdot \frac{V_{REF}}{V_{OUT}}$
OPEN LOOP* GAIN OF THE CURRENT LIMIT LOOP	$A_{OC} = \frac{Z_C}{300} \cdot \frac{1}{R_D + 12} \cdot \beta_{Q1} \cdot R_S$	$A_{OC} = \frac{Z_C}{300} \cdot \frac{1}{12/\beta_{Q1} + Z_O} \cdot R_S$	$A_{OC} = \frac{Z_C}{300} \cdot \frac{1}{R_D + 12} \cdot \beta_{Q1} \cdot \beta_{Q2} \cdot R_S$	$A_{OC} = \frac{Z_C}{300} \cdot \frac{1}{12/\beta_{Q1} + Z_O} \cdot R_S$

* Z_C = IMPEDANCE AT COMPENSATION PIN, PIN 14. Z_O = IMPEDANCE AT CHARGER OUTPUT

FIGURE 12. There are a large number of possible driver/pass element configurations, a few are summarized here. The trade-offs are between current gain, input to output differential, and in some cases, power dissipation on the UC3906. When dissipation is a problem it can be reduced by adding a resistor in series with the UC3906 driver.

(see figure 12). These resistors will then share the power with the die. The charger parameters most affected by increased driver dissipation are the transition thresholds, (V_{12} and V_{21}), since the charger is, by design, supplying its maximum current at these points. The current levels will not be affected since the input offset voltages on the current amplifier and sense comparator have very little temperature dependence. Also, the stand-by float level on the charger will still track ambient temperature accurately since, normally, very little current is required of the charger during this condition.

To estimate the effects of dissipation on the charger's voltage levels, calculate the power dissipated by the IC at any given point, multiply this value by the thermal resistance of the package, and then multiply this product by $-3.9\text{mV}/^\circ\text{C}$ and the proper external divider ratio. In most cases, the effect can be ignored, while in others the charger design must be tweaked to account for die dissipation by adjusting charger parameters at critical points of the charge cycle.

SOME RESULTS WITH THE DUAL LEVEL FLOAT CHARGER

In figure 13 the schematic is shown for a dual level, float charger designed for use with a 6V, 2.5amp-hour, sealed lead-acid battery. The specifications, at 25°C , for this charger are listed below.

- Input supply voltage 9.0V to 13V
- Operating temperature range 0°C to 70°C
- Start-up trickle current (I_T) $10\mu\text{A}$ ($V_{IN} = 10\text{V}$)
- Start-up voltage (V_T) 5.1V
- Bulk charge rate (I_{MAX}) 500mA (C/5)
- Bulk to OC transition voltage (V_{12}) . . 7.125V
- OC voltage (V_{OC}) 7.5V
- OC terminate current (I_{OCT}) $50\mu\text{A}$ (C/50)
- Float voltage (V_F) 7.0V
- Float to Bulk transition voltage (V_{31}) 6.3V
- Temperature coefficient on voltage levels $-12\text{mV}/^\circ\text{C}$
- Reverse current at charger output with the input supply at 0.0V $\leq 5\mu\text{A}$

In order to achieve the low input to output differential, (1.5V) the charger was designed with a PNP pass device that can operate in its saturation region under low input supply conditions. The series diode, required to meet the reverse current specification, accounts for 1.0V of the 1.5V minimum differential. Keeping the reverse current under $5\mu\text{A}$ also requires the divider string to be disconnected when input power is removed. This is accomplished, as discussed earlier, by using the input power indicate pin to reference the divider string.

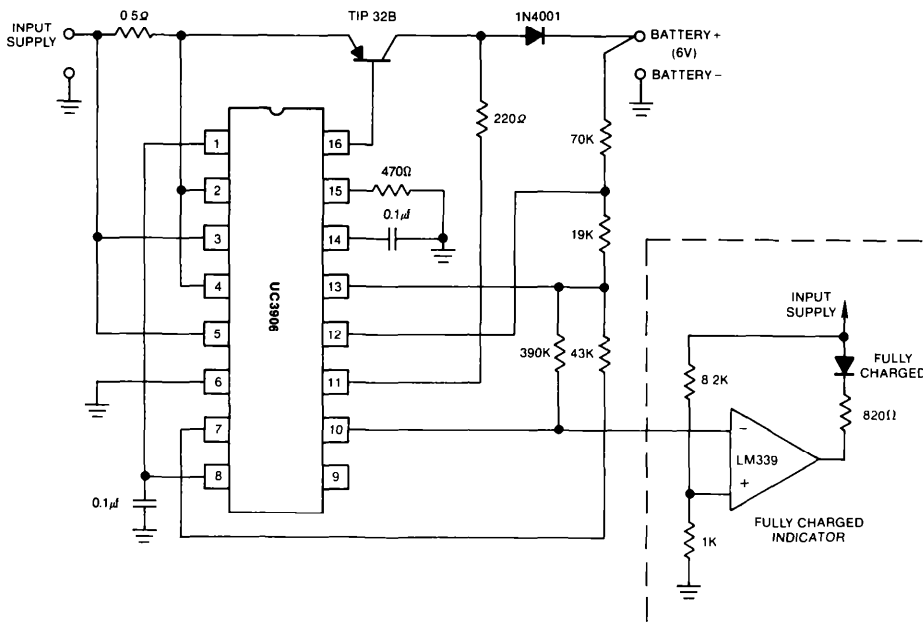


FIGURE 13. This dual level float charger was designed for a 6V (three 2V cells) 2.5AH battery. A separate "fully charged" indicator was added for visual indication of charge completion.

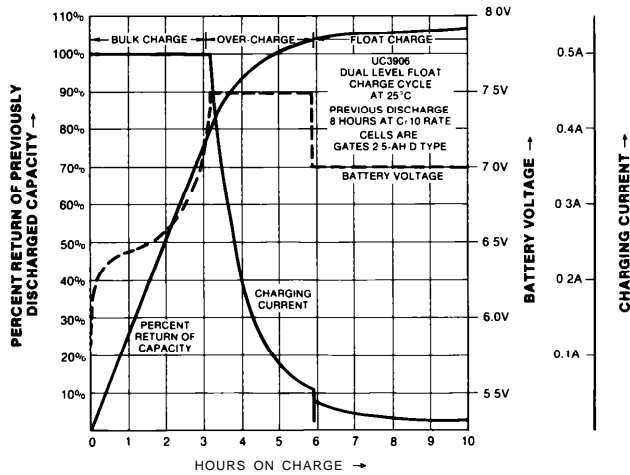


FIGURE 14. The nearly ideal characteristics of the dual level float charger are illustrated in these curves. The over-charge state is entered at about 80% return of capacity and float charging begins at just over 100% return.

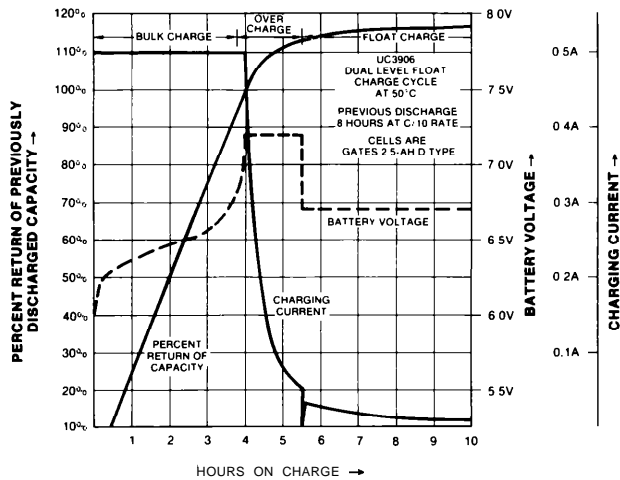


FIGURE 15. At elevated temperatures the maximum capacity of lead-acid cells is increased allowing greater charge acceptance. To prevent excessive over-charging though, the charging voltage levels are reduced.

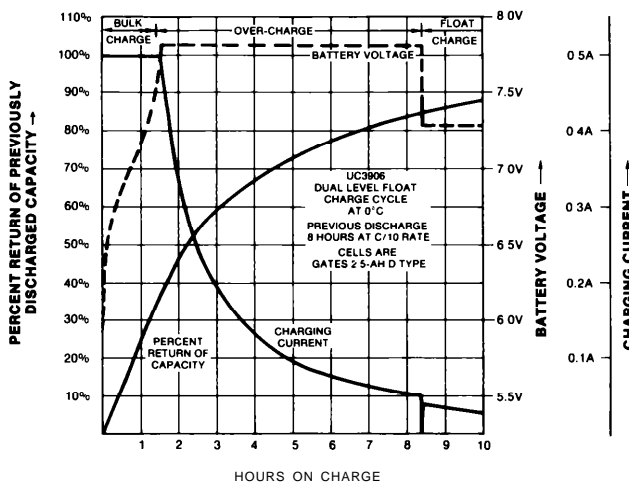


FIGURE 16. At lower temperatures the capacity of lead-acid cells is reduced as reflected by the less-than-100% return of capacity in this 0°C charge cycle, illustrating the need for elevated charging voltages to maximize returned capacity.

The driver on the UC3906 shunts the drive current from the pass device to ground. The 470ohm resistor added between PIN 15 and ground keeps the die dissipation to less than 100mW under worst case conditions, assuming a minimum forward current gain in the pass element of 35 at 500mA.

The charger in figure 13 includes a circuit to detect full charge and gives a visual indication of charge completion with an LED. This circuit turns on the LED when the battery enters the float state. Entering of the float state is detected by sensing when the state level output turns-off.

Figures 14-16 are plots of charge cycles of the circuit at three temperatures, 25°C, 50°C and 0°C. The plots show battery voltage, charge rate, and percent return of previously discharged capacity. This last parameter is the integral of the charge current over the time of the charge cycle, divided by the total charge volume removed since the last full charge. For all of these curves the previous discharge was an 80% discharge, (2amp-hours), at a C/10, (250mA), rate. The discharges were preceded by an over-night charge at 25°C.

The less than 100% return of capacity evident in the charge cycle at 0°C is the result of the battery's reduced capacity at this temperature. The tapering of the charge current in the over-charge state still indicates that the cells are being returned to a full state of charge.

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