IMPLEMENTING MULTI-STATE CHARGE ALGORITHM WITH THE UC3909 SWITCHMODE LEAD-ACID BATTERY CHARGER CONTROLLER

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INTRODUCTION

Applications of lead-acid batteries for primary as well as backup power sources has been increased significantly. The reasons behind this growth are the continuously improving battery technology which provides higher and higher power densities, and the increased demand for wireless operation of different electronic devices and tools. Manufacturers of these equipment are frequently challenged to provide solutions for quick and efficient recharge of the cells and to maximize the capacity and life of the battery.

Although the task sounds simple, satisfying the various requirements associated with charging and maintaining lead-acid batteries often requires considerable intelligence from the battery charger circuit. The implementation of a well optimized charging process requires complex control circuitry, such as microprocessors, DSP chips or state machine type of controllers. Usually, these solutions require custom components, and significant hardware and software development time. The cost of these solutions are penalized, by the higher cost and software of the digital controller, interfacing to the analog part of the circuit, in addition to the increased part count and consequently higher manufacturing expense.

This Application Note will introduce a new, dedicated analog controller. The UC3909 Switchmode Lead-Acid Battery Charger integrated circuit provides a low cost solution to battery charging, without sacrificing the performance of the system.

Additionally, the paper will guide users, whose primary expertise is not switchmode power supply design, how to devise state of the art, multi-state battery charger, using the new IC. The step by step instructions incorporated in this Application Note will provide exact component values, reducing the time of the paper design to merely a few minutes.

BASICS OF LEAD-ACID BATTERIES

In order to efficiently discuss battery properties, some of the common terms used in the battery industry have to be defined.

Ampere-Hour (Ah) - is a measurement of electric charge computed as the integral product of current (in Amperes) and time (in hours).

Capacity - is the ability of the battery to store and discharge a given quantity of current over a specified period of time. The capacity of the battery is expressed in Ampere-Hours (Ah). A cell's capacity is a function of the discharge current and usually increases with lower current levels. The capacity of the battery listed in the datasheet usually corresponds to the measured capacity at C/10 discharge rate.

C Rate - is the charge or discharge current of the battery expressed in multiples of the rated capacity. For example, a 2.5Ah cell will provide 250mA for 10 hours. The C rate in this particular case is C/10. In the real world, however, a cell does not maintain the same rated capacity at all C rates.

Self Discharge - is the loss of useful capacity of a cell on storage due to internal chemical action.

Deep Discharge - is the discharge of the battery below the specified cutoff voltage, typically 1.7V-1.9V per cell at 25°C depending on the C rate, before the battery is recharged. It happens usually upon withdrawal at least 80% of the rated capacity of the cells.

Constant Voltage Charge - is a charging technique during which the voltage across the battery terminals is regulated while the charge current varies according to the state of charge of the battery.

Constant Current Charge - is a charging method during which the current through the battery is maintained at a steady state value while the cell

voltages will vary according to the state of charge of the battery.

Trickle-Charge - is a constant current charge of the battery. In this mode, a low current, typically in the range of C/100 or lower is applied to the battery to raise the voltage to the deep discharge threshold (cutoff voltage), a level corresponding to near zero capacity. The trickle charge current has to be determined to assure continuous operation without damaging the cells.

Bulk-Charge - is also a constant current mode of operation, to quickly replenish the charge to the battery. The battery manufacturers define the bulk charge current as the maximum charge current allowed for the cells. It can be applied to the batteries if their voltage is between the deep discharge and the over-charge limits. Typical bulk charge current varies between C/5 and 2·C depending on manufacturers and battery types.

Over-Charge - the term describes the chemical reactions taking place when the majority of the lead-sulfate has already been converted to lead, resulting in the generation of hydrogen and oxygen. The beginning of the over-charge reactions depends on the C rate, and it is indicated by the sharp rise in cell voltage as it is illustrated in Figure 1.
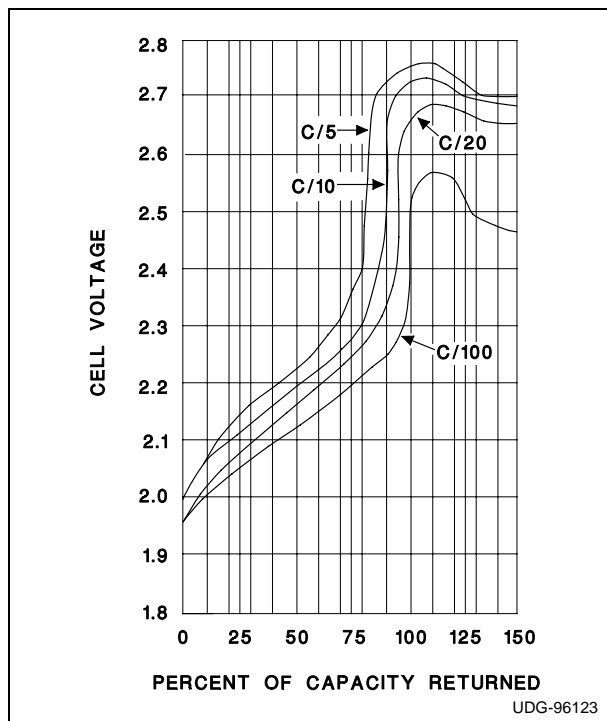
Figure 1. Typical over-charge characteristic at different charge rates.

For over-charge to coincide with the 100% return of capacity, the charge rate must be less than C/100. For higher charge rates, over-charge of lead-acid batteries is necessary to return the full capacity.

In a controlled **over-charge mode**, a constant voltage is applied. Its value is typically set between 2.45 V/cell and 2.65 V/cell, again depending on the C rate. Improper selection of the over-charge voltage will eventually result in dehydration of the battery and reducing its useful life span.

Float-Charge - is a constant voltage charge of the battery, after completing the charging process. This voltage maintains the capacity of the battery against self discharge. Even though providing a fixed output voltage is a simple task, to find the precise value of the float voltage has a profound effect on battery performance. For instance, 5% deviation from the optimum cell voltage in float mode, could result approximately 30% difference in the available capacity of the battery. Furthermore, the battery's temperature coefficient of typically -3.9mV/°C per cell, adds complication. If the float voltage is not compensated according to the battery temperature, loss of capacity will occur below the design temperature, and uncontrolled over-charging with degradation in life will happen at elevated temperature.

BATTERY CHARGER BASICS

What differentiates a battery charger from a conventional power supply is the capability to satisfy the unique requirements of the battery. Lead-acid battery chargers typically have two tasks to accomplish. The most important is to restore capacity as quickly as possible. The second one is to maintain capacity by compensating for self discharge and ambient temperature variations.

There are two fundamentally different charging methods for lead-acid batteries. In constant voltage charge, the voltage across the battery terminals is constant and the condition of the battery determines the charge current. Constant voltage charge is most popular in float mode application. The charging process is usually terminated after a certain time limit is reached.

Another technique is constant current charge, which is often used in cyclic applications because it recharges the battery in a relatively short time. As opposed to constant voltage charge, the constant current charge automatically equalizes the charge in the series cells. There are many varia-

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tions of the two basic methods, well suited for switchmode battery charger circuits. Considering that well designed switchmode power converters are inherently current limited, the combination of constant current and constant voltage charge is an obvious choice.

The best performance of the lead-acid cells can be achieved using a four state charge algorithm. This method integrates the advantages of the constant current charge to quickly and safely recharge and equalize the lead-acid cells, with the constant voltage charge to perform controlled over-charge and to retain the battery's full charge capacity in float mode applications. The carefully tailored charging procedure maximizes the capacity and life expectancy of the battery.
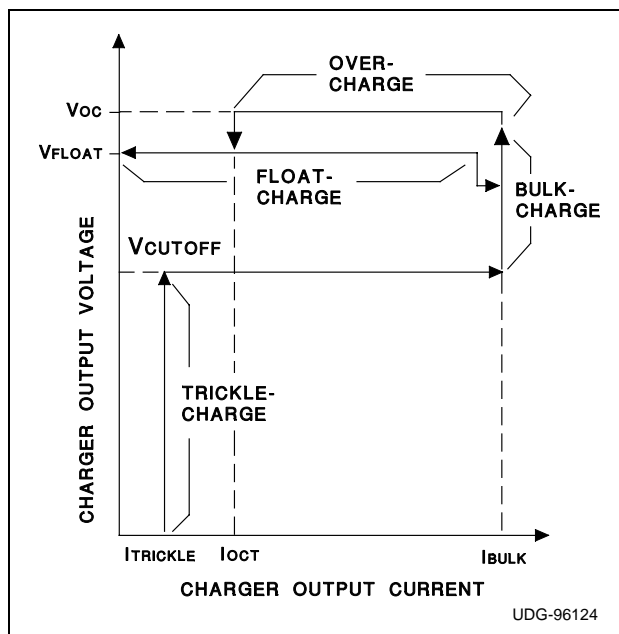
Figure 2. Four-state charge algorithm

The four states of the charger's operation are trickle charge, bulk charge, over-charge and float charge, as they are shown in Figure 2. Assuming a fully discharged battery, the charger sequences through the states as follows:

State 1: Trickle Charge
If the battery voltage is below the cutoff voltage, the charger will apply the preset trickle charge current ($I_{TRICKLE}$). In case of a healthy battery, as the charge is slowly restored, the voltage will increase towards the nominal range until it reaches the cutoff voltage. At that point the charger will advance to the next state, bulk charging.

In case of a damaged battery, e.g. one or more cells are shorted or the internal leakage current of the battery is increased above the trickle current value, the low value of the trickle charge current ensures safe operation of the system. In this case the battery voltage will stay below the deep discharge threshold (V_{CUTOFF}) preventing the charger from proceeding to the bulk charge mode.

When the battery voltage is above the cutoff voltage at the beginning of the charge cycle, the trickle charge state is skipped and the charger starts with the bulk charge mode.

State 2: Bulk Charge
In this mode the maximum allowable current (I_{BULK}) charges the battery. During this time, the majority of the battery capacity is restored as quickly as possible. The bulk charge mode is terminated when the battery voltage reaches the over-charge voltage level (V_{OC}).

State 3: Over-Charge
Controlled over-charge follows bulk charging to restore full capacity in a minimum amount of time. During the over-charge period, the battery voltage is regulated. The initial current value equals the bulk charge current, and as the battery approaches its full capacity the charge current tapers off. When the charge current becomes sufficiently low (I_{OCT}), the charging process is essentially finished and the charger switches over to float charge. The current threshold, I_{OCT}, is user programmable and is typically equals $I_{BULK}/5$.

State 4: Float Charge
This mode is only applicable when the battery is used as a backup power source. The charger will maintain full capacity of the battery by applying a temperature compensated DC voltage across its terminals. In the float mode, the charger will deliver whatever current is needed to compensate for self discharge and might supply the prospective load up to the bulk charge current level. If the primary power source is lost or if the load current exceeds the bulk current limit, the battery will supply the load current. When the battery voltage drops to 90% of the desired float voltage, the operation will revert to the bulk charge state.

The ultimate lead-acid battery charger will combine the above described four state charge algorithm, and particularly at higher output currents, a switchmode power converter. The implementation of a charger of this type usually requires several

integrated circuits. To minimize cost as well as complexity, a new integrated circuit had been developed to provide as much functionality and design flexibility as possible, while achieving these requirements.

THE UC3909 BLOCK DIAGRAM

The UC3909 Switchmode Lead-Acid Battery Charger controller combines the precision sensing and control of battery voltage and current, logic to sequence the charger through its various modes of operation, and the control and supervisory functions of a switching power supply. The integrated circuit comprises of two major sections. A dashed line shown in the middle of Figure 3 divides the circuit into two functional subsections. The PWM control circuit is commanded by the charge state logic depending on the condition of the battery.

The charge state logic is shown in the lower right corner of the block diagram, which is composed of several digital gates. It sequences the charger through the four possible states of operation depending on the battery voltage. Information about

the actual operating mode of the charger is also provided. The status information can be easily interfaced to any logic family due to the open collector structure of the outputs of pin STAT0, STAT1, and STATLV. (See the datasheet for detailed pin descriptions.)

The precision voltage and current sensing circuits are shown in the lower left corner of the block diagram. The battery voltage is compared to the temperature compensated reference voltage by the voltage error amplifier and charge enable comparator. Accurate sensing of the charge current is achieved by the uncommitted current sense amplifier, connected to the CS+, CS- and CSO pins. The use of this amplifier requires a low value resistor for current measurement. Output regulation is accomplished by the current error amplifier. Its inverting and noninverting inputs are connected to the output of the current sense and voltage error amplifiers through external resistors. The output of the current error amplifier produces the appropriate control parameter for the PWM controller.
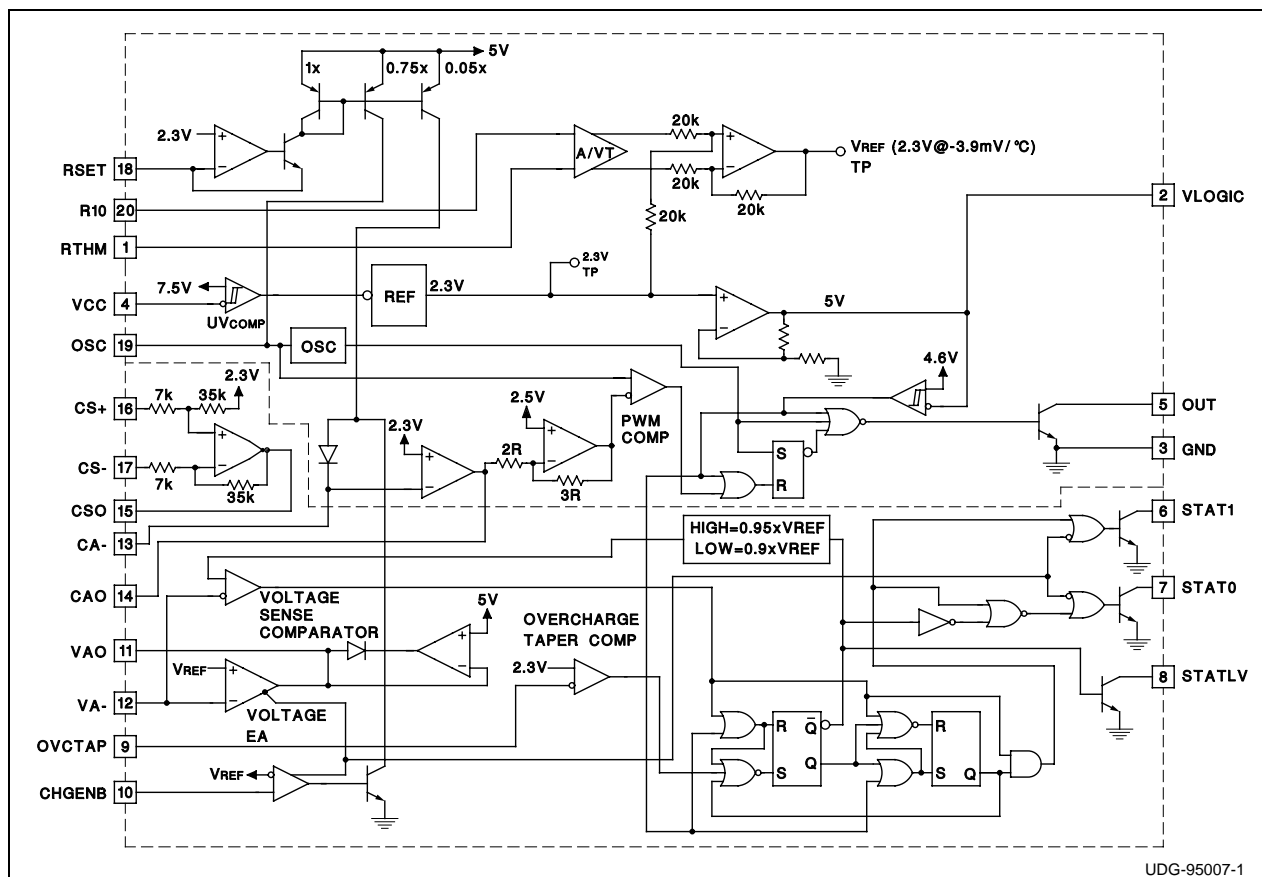

Figure 3. UC3909 Block Diagram

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The PWM control section consists of a fast comparator, clock generator, latch and an open collector drive stage. The comparator circuit compares the output of the current error amplifier to the sawtooth derived from the timing capacitor waveform. A latch is set by the clock and reset by the comparator circuit in every switching cycle modulating the pulse width appearing at the output of the controller. This modulation of the output pulse width makes output voltage and output current regulation possible.

The remaining part of the block diagram performs numerous housekeeping functions, such as undervoltage lockout, internal bias and reference generation, temperature sensor linearization and compensation of the internal voltage reference according to the battery temperature.

UC3909 DEMONSTRATION CIRCUIT

To illustrate the capabilities of the new controller, a full featured, switchmode battery charger circuit has been developed and built for evaluation purposes.

The power stage is based on a simple buck topology, reflecting the most common solution used in battery chargers today. The buck converter offers size reduction and high efficiency, two important advantages of switchmode power conversion. Practical output power of this converter type is below 500W. In the case of off-line chargers, line isolation can be provided by 60Hz isolation transformer. For higher power levels the buck converter could be easily replaced by other isolated, buck derived topologies, like any variation of the forward or bridge type converters. Using one of these isolated conversion techniques will eliminate the bulky 60Hz transformer by integrating the isolation into the high frequency power stage. The design procedure, that will be presented in this Application Note for the buck configuration, can be easily adapted to the other power converters.

The usual elements of the buck converter can be recognized in Figure 4. They are Q1, D2, L1 and C5. Other components in the power stage pertain to additional, application specific requirements. D1 prevents the discharge of the battery by the con-
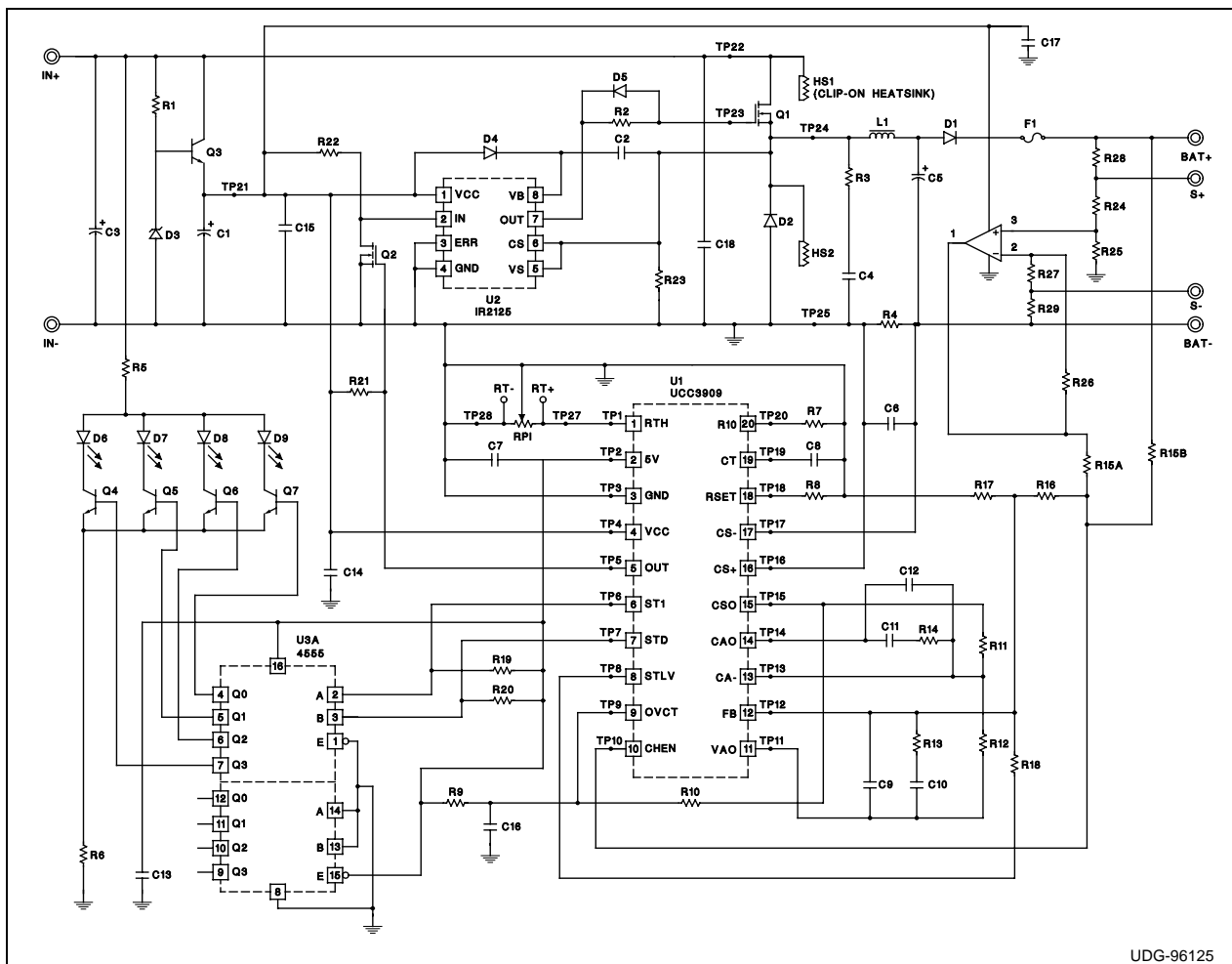
Figure 4.   Demonstration Board Schematic

troller, when the primary power source is absent. An output fuse, F1, protects the circuit against the possible hazards when the battery is connected to the output terminals with reverse polarity. The charge current is measured by the resistor, R4 in the ground return path. The controller section consists of four well separable circuits. The first functional block is composed of R1, D3, Q3, and C1. These components provide a stabilized voltage for the rest of the control circuitry.

In the buck converter, the controlled switch, Q1, is located between the positive input terminal and the common node of the freewheeling diode, D2, and the output filter inductor, L1. There are many different components which could be used as a switch, yet for efficient operation and cost considerations, an N-channel MOSFET transistor has been selected. To interface the floating switch to the ground referenced controller, a high side driver is inevitable. The high side driver circuit consists of U2, D4, D5, R2, C2, Q2, R22 and R23. Its purpose is to level shift the output pulse of the control IC to the gate of the MOSFET transistor with minimum delays.

All the functions related to properly charging the battery are integrated in the UC3909 controller. The voltage and current levels which determine the actual values of the cutoff, over-charge and float voltages, as well as the trickle, bulk and taper threshold currents, are scaled appropriately by the resistor networks around the IC. The role of those components will be defined in the next chapter deliberating the design procedure.

The last section is the charge state decoder circuit. The coded information of the two outputs of the UC3909 is translated by U3, to display the actual operating mode of the battery charger.

BATTERY CHARGER DESIGN

The complete schematic drawing of the four state, switchmode battery charger is shown in Figure 4. In order to expedite the paper design, an easy to follow design procedure has been established. The step by step instructions can guide even the novice users through the calculations.

Battery Data

By the time the designer starts the circuit design, the type of the battery is already defined. The battery selection criteria are not detailed in this Application Note. Nevertheless, it is worthwhile to draw attention to some of the circumstances influencing the decision. Naturally, the most important parameters are the voltage and current requirements of the load as well as the time duration while the battery has to be able to supply the load current. Furthermore, the user has to consider whether the application requires frequent charge and discharge cycles or the battery is used in backup mode, where most of the time it will standby in its fully charged state. The available time for recharging the battery is also a significant factor to determine the applicable algorithm, and charge current rates. Combination of all these conditions will define the required battery and some of the battery charger parameters.

Once the battery is defined we can obtain the first set of input data. From the battery manufacturer's data sheet, more frequently through several telephone calls, and considering some application related conditions, the lines of Table 1 can be filled out.

For example, the demonstration circuit has been designed to charge a Dynasty JC1222 type sealed lead-acid battery from Johnson Controls. The nominal voltage is 12V, the capacity of the battery is 2.2Ah. Twelve volt batteries contain six cells connected in series. The battery has a temperature coefficient of -3.9mV/°C. Additional input parameters, like operating temperature range, float, cutoff and over-charge voltages as well as trickle, bulk, and over-charge terminate current levels can be determined from the application requirements and from the battery data sheet.

The completed Battery Data section is shown in Table 1. The trickle current level corresponds to the previously explained safety considerations and it equals C/100. A bulk charge current value of 800mA is given by the battery manufacturer [8] and is used instead of the C/2 value, noted in the respective equation in Table 1.

The over-charge period will be terminated when the current tapers off to one fourth of the bulk current. Maximum output power of the battery charger is listed in the last row of Table 1.

Parameter	Description	Definition	Value/Part#
Battery Data			**JC1222**
V	Nominal Battery Voltage		12V
NC	Number Of Cells	connected in series within the battery	6
C_{RATE}	Battery Capacity	use C/10 capacity; from battery datasheet	2.2 Ah
V_C	Cell Float Voltage	@25°C, fully charged; from battery datasheet	2.275V
$V_{C,MAX}$	Maximum Cell Voltage	@25°C, over-charge limit; from battery datasheet	2.43V
$V_{C,MIN}$	Minimum Cell Voltage	@25°C, fully discharged; from battery datasheet	1.75V
$I_{TRICKLE}$	Trickle Charge Current Limit	$I_{TRICKLE} = 0.01 \cdot C_{RATE}$; typical or use battery datasheet	22mA
I_{BULK}	Bulk Charge Current Limit	$I_{BULK} = 0.5 \cdot C_{RATE}$; typical or use battery datasheet	0.8A
I_{OCT}	Over-Charge Terminate Current Threshold	$I_{OCT} = 0.25 \cdot I_{BULK}$; typical or use battery datasheet	0.2A
TC	Cell Voltage Temperature Coefficient	typical value; the thermistor linearizer circuit is calibrated for this temperature coefficient	-3.9 mV/°C
T_{MIN}	Minimum Operating Battery Temperature	refer to your application requirements	-10°C
T_{MAX}	Maximum Operating Battery Temperature	refer to your application requirements	+50°C
V_{BAT}	Battery Float Voltage	$V_{BAT} = V_C \cdot NC$; nominal, @ 25°C battery temperature	13.65V
$V_{BAT,MIN}$	Minimum Battery Voltage	$V_{BAT,MIN} = \left[V_{C,MIN} + \left(T_{MAX} - 25 \right) \cdot TC \right] \cdot NC$; @ T_{MAX}; fully discharged	9.92V
$V_{BAT,MAX}$	Maximum Battery Voltage	$V_{BAT,MAX} = \left[V_{C,MAX} + \left(T_{MIN} - 25 \right) \cdot TC \right] \cdot NC$; @ T_{MIN}; fully charged	15.40V
$P_{CH,MAX}$	Maximum Output Power	$P_{CH,MAX} = I_{BULK} \cdot V_{BAT,MAX}$	12.3W

Table 1. Battery Charger Input Parameters

Buck Converter Operating Conditions

The battery charger circuit of the UC3909 is based on the buck topology. Before the component values of the power stage can be calculated, the basic operating parameters must be defined.

The output voltage range is listed in Table 1 as $V_{BAT,MIN}$ and $V_{BAT,MAX}$ determined primarily by the operating temperature range and the battery technology. On the other hand, input voltage variation depends on the power source. For this particular example, assume a 60Hz line isolation transformer with the optimized step down ratio. At minimum line voltage, it provides 18V DC voltage after rectification. Taking into account nominal tolerances, the input voltage of the converter at high line condition will be approximately 30V DC. From the minimum and maximum values of the input and output voltages, the steady state duty ratio limits are calculated (D=0.37 ... 0.89) as shown in Table 2.

At this point, the switching frequency of the converter has to be chosen. The trade-offs involved in the frequency selection are numerous. The primary factors are the speed of the prospective semiconductors, the capabilities of the controller, maintaining high efficiency in wide load current variations, power level and the size of the output inductor and capacitors.

Parameter	Description	Definition	Value/Part#
Buck Converter Operating Parameters			
$V_{IN,MIN}$	Minimum Input Voltage		18V
$V_{IN,MAX}$	Maximum Input Voltage		30V
f_S	Switching Frequency		50kHz
V_{D1F}	D1 Diode Forward Voltage Drop (estimate)	@100°C with I_{BULK}	0.59V
V_{D2F}	D2 Diode Forward Voltage Drop (estimate)	@100°C with I_{BULK}	0.73V
D_{MAX}	Maximum Duty Ratio	$D_{MAX} = \dfrac{V_{BAT,MAX} + V_{D1F} + V_{D2F}}{V_{IN,MIN} + V_{D2F}}$	0.89
D_{MIN}	Minimum Duty Ratio	$D_{MIN} = \dfrac{V_{BAT,MIN} + V_{D1F} + V_{D2F}}{V_{IN,MAX} + V_{D2F}}$	0.37

Table 2. Buck Converter Operating Parameters

For example, the upper limit of the operating frequency is bound to the capabilities of the slowest components. In the demonstration circuit, the high side gate driver circuit can be conveniently operated up to 150kHz operating frequency. Since the buck converter is a hard switched topology, the operating frequency has a significant effect on the efficiency. Considering that most of the time the charger supplies light output load, further reduction of the switching frequency is desirable to maintain decent efficiency in this operating modes.

While reducing the switching frequency has a beneficial effect on efficiency, at the same time the size of the output inductor and capacitors are increasing. The compromise between the size of the reactive circuit components and light load efficiency in trickle and float charge modes led to a moderate switching frequency selection of 50kHz.

Power Stage Design

Table 3 summarizes the design procedure of the power components. The bold entries shall be copied over to the part list directly. The respective equations are included, and they make use of variables defined in Table 1 and Table 2, or by the previous lines in Table 3.

Semiconductors

First, the three semiconductor devices are selected. Their voltage and current ratings are based on the maximum input and output voltages and on the bulk charge current. The minimum current ratings given in Table 3 assure appropriate margins for reliable operation. Using higher current components improves efficiency but also might increase cost.

After the part number is chosen, power dissipation estimates are given based on the actual voltage, current, and device parameters. The diode D1 carries the DC output current, therefore its dissipation is strictly conduction loss. The other two semiconductors are part of the switching circuit, hence their power dissipation is calculated by adding their respective conduction and switching losses.

Note that estimating switching losses on device parameters can be fairly inaccurate. This can cause a significant difference between the estimated and real switching losses especially at higher operating frequencies.

Output Inductor

The inductance of the output choke has been calculated by choosing the maximum ripple component of the inductor current. In a general purpose buck converter, unless extreme noise, core loss or application specific requirements would dictate otherwise, the rule of thumb is 25% to 35% of the DC current value is acceptable for ripple current content. Although battery manufacturers are concerned about using AC currents to charge the battery, they usually refer to frequencies below 1kHz. The DC output current with superimposed AC components of the switchmode chargers, at considerably higher frequencies, will be averaged by the slow chemical processes inside the battery.

Input Capacitor

The value of the input energy storage capacitor depends on the tolerable ripple and noise voltage at the input of the converter, and a function of the hold-up requirements. It is especially important for AC operated chargers where the energy is avail-

able in 120Hz repetitions, while the output has to be supplied continuously.

The situation is somewhat different if the charger is part of a distributed power system where an already regulated voltage with reasonable energy storage capability is available for the circuit. In this case, the ripple current handling capability of C3, and the noise requirements will determine the value of the input capacitor.

In Table 3, the value of the selected input capacitor is based on its rms current handling capability. The UC3909 demonstration circuit will operate properly when it is connected to a laboratory power supply, but will require a larger input capacitance in off-line applications.

Output Capacitor

There are numerous factors determining the output capacitor value. The various noise requirements at the output of the converter, the acceptable output voltage sag during the time interval when the capacitor contributes to supply the load current, and loop stability criteria. Fortunately, for all practical purposes, the output capacitor of a battery charger loses its importance since it is connected in parallel with the battery. The battery is considered as a low impedance voltage source with great high frequency filtering capabilities, taking over the traditional functions of the output capacitor.

The output capacitor, C5 of the demonstration circuit was chosen to handle the rms value of the ripple current component in the output inductor, L1 and to provide appropriate filtering in the absence of the battery.

RC Damping Circuit

Due to the nonideal nature of the switching action in all hard switching topologies, excessive switching spikes can develop across the semiconductors of the circuit during the switching time interval. The reduction of this voltage stress is accomplished by an RC snubber circuit consisting of R3 and C4 of the demonstration circuit. The complex optimization of the RC network is assisted by reference [6]. Proper operation of the snubber circuit also depends on the layout and the parasitic components of the switching circuit. Table 3 gives two equations to calculate the component values of R3 and

C4 as a starting point. Further optimization of these component values might be desirable based on measurement results.

Note, that a tight layout of the critical components C18, Q1 and D2, and using an ultra fast rectifier diode are also essential to keep unwanted switching spikes under control.

Current Sense

The accurate control of the output current is one of the most important functions of the battery charger. It is achieved by the UC3909 control IC using average current mode control. An exact measurement of the current flowing in the output inductor, L1 is required. Therefore, a low value current sense resistor, R4 is placed in the ground return path, between the anode of D2 and the negative electrode of the output capacitor, C5. The voltage developed across R4 is proportional to the inductor current, and used by the controller to regulate the trickle and bulk charge current levels as well as to provide current limiting during overload operation.

The value of the current sense resistor is determined to satisfy two conditions. The first constraint is to limit the maximum voltage across R4 below 350mV when full output current is delivered. This is required by the UC3909 to prevent the current sense amplifier from saturation. The second restriction is the power dissipation of R4. In Table 3, the power dissipation of the current sense resistor was set to 1.5% of the maximum output power. This assumption was made to balance between two opposing requirements, namely to maintain high efficiency and to provide the highest signal level across R4, thus to improve noise immunity of the circuit. The maximum power dissipation equation of R4 might have to be revised, especially in higher power applications, due to component ratings and efficiency considerations.

Output Fuse

The fuse in series with the output of the battery charger is intended to prevent catastrophic failure if the battery is connected to the charger with reversed polarity. The fuse has to be selected with sufficient safety margin to carry the full charge current, but disconnect the output quickly in case of excessive currents drawn from the battery.

Parameter	Description	Definition	Value/Part#
Power Stage Design			
V_{RMM} (D1)	Diode Breakdown Voltage (minimum)	$V_{RRM} = 1.5 \cdot V_{BAT,MAX}$ (pick the next higher standard value)	(23.1V) 50V
$I_{O,MIN}$ (D1)	Diode Current Rating (minimum)	$I_{O,MIN} = 2 \cdot I_{BULK}$	1.6A
D1	Discharge Protection Diode	Select general purpose diode.	**GI750CT**
P_{D1}	Diode Power Dissipation (approximate value for heatsink selection)	$P_{D1} = I_{BULK} \cdot V_{D1F}$ (assuming $100°C$ junction temperature)	0.5W
V_{RMM} (D2)	Diode Breakdown Voltage (minimum)	$V_{RRM} = 1.5 \cdot V_{IN,MAX}$ (pick the next higher standard value)	(45V) 50V
$I_{O,MIN}$ (D2)	Diode Current Rating (minimum)	$I_{O,MIN} = 2 \cdot I_{BULK}$	1.6A
D2	Buck Freewheeling Diode	Select ultra fast switching diode.	**MUR610**
t_{RR}	Diode Reverse Recovery Time	catalog data; @ I_{BULK} ; approximate value	35ns
I_{RRM}	Diode Peak Reverse Recovery Current	catalog data; @ I_{BULK} ; approximate value	0.5A
P_{D2}	Diode Power Dissipation (approximate value for heatsink selection)	$P_{D2} = I_{BULK} \cdot (1 - D_{MIN}) \cdot V_{D2F} +$ $+ 0.25 \cdot I_{RRM} \cdot V_{IN,MAX} \cdot t_{RR} \cdot f_S$	0.38W
V_{DSS} (Q1)	Switch Breakdown Voltage (minimum)	$V_{DSS} = 1.5 \cdot V_{IN,MAX}$ (pick the next higher standard value)	(45V) 50V
$I_{D,MIN}$ (Q1)	Transistor Current Rating (minimum)	$I_{D,MIN} = 4 \cdot I_{BULK}$	3.2A
Q1	Buck Main Switch	Select the MOSFET transistor	**IRFZ14**
R_{DSON} (Q1)	Switch ON Resistance	catalog data; @$25°C$, typical value	200mΩ
C_{OSS} (Q1)	Drain Source Capacitance	catalog data; typical value	160pF
I_{GATE}	Gate Charge/Discharge	approximate, average value	0.8A
Q_{GS} (Q1)	Gate-To-Source Charge	catalog data	3.1nC
Q_{GD} (Q1)	Gate-To-Drain Charge	catalog data	5.8nC
t_{OFF}; t_{ON}	Approximate Switching Times	$t_{OFF} = t_{ON} = \dfrac{Q_{GS} + Q_{GD}}{I_{GATE}}$	12ns
P_{Q1}	Switch Power Dissipation (approximate value for heatsink selection)	$P_{Q1} = I_{BULK}^2 \cdot D_{MAX} \cdot R_{DSON} \cdot 1.5 +$ $+ 0.5 \cdot C_{OSS} \cdot V_{IN,MAX}^2 \cdot f_S +$ $+ \dfrac{V_{IN,MAX} \cdot I_{BULK}}{2} \cdot (t_{OFF} + t_{ON} + t_{RR}) \cdot f_S$	0.21W
P_{HS}	Heatsink Power Dissipation	$P_{HS} = P_{D1} + P_{D2} + P_{Q1};$ worst case, estimate	1.1W
$\Delta I_{L,MAX}$	Inductor Ripple Current	$\Delta I_{L1,MAX} = 0.4 \cdot I_{BULK};$ typical value	0.32A
L1	Buck Inductance	$L1 = \dfrac{V_{IN,MAX}}{\Delta I_{L1,MAX} \cdot 4 \cdot f_S}$	(0.47mH) **0.4mH**
$I_{L1,PEAK}$	Inductor Peak Current	$I_{L1,PEAK} = I_{BULK} + \dfrac{V_{IN,MAX}}{8 \cdot L1 \cdot f_S}$	**1A**
L1	Buck Filter Inductor	Check vendor's list for off the shelf part number or design you inductor according to the values above	**PCV-2-400-05** (Coiltronics)

Parameter	Description	Definition	Value/Part#
V_{C3}	Input Capacitor Voltage Rating	$V_{C3} = 1.5 \cdot V_{IN,MAX}$ (pick the next higher standard value)	(45V) 50V
$I_{C3,RMS}$	Input Capacitor RMS Current	$I_{C3,RMS} = 0.5 \cdot I_{BULK}$ (worst case @ f_S; D=0.5)	0.4A
C3	Input Capacitor (electrolytic)	High frequency type, i.e. Panasonic HFQ series (see text for value considerations)	**680µF/35V**
C18	High Frequency Bypass Capacitor For Switches	Polypropylene or stacked metallized film. Minimum voltage rating equals V_{C3}.	**1µF/63V**
V_{C5}	Output Capacitor Voltage Rating	$V_{C5} = 1.5 \cdot V_{BAT,MAX}$ (pick the next higher standard value)	(23.1V) 25V
$I_{C5,RMS}$	Output Capacitor RMS Current	$I_{C5,RMS} = \dfrac{V_{IN,MAX}}{\sqrt{192} \cdot f_S \cdot L1}$	108mA
C5	Output Capacitor (electrolytic)	High frequency type, i.e. Panasonic HFQ series (see text for value considerations)	**470µF/25V**
$R_{C5,ESR}$	Output Capacitor's ESR	from datasheet	65mΩ
$P_{SN,MAX}$	Snubber Power Dissipation	$P_{SN,MAX} = P_{CH,MAX} \cdot 0.015$ assume 1.5% of full output power	0.185W
V_{C4}	Snubber Capacitor Voltage Rating	$V_{C4} = 1.5 \cdot V_{IN,MAX}$ (pick the next higher standard value)	(45V) 63V
C4	Snubber Capacitor (polypropylene or metallized film)	$C4 = \dfrac{2 \cdot P_{SN,MAX}}{V_{IN,MAX}^2 \cdot f_S}$ (pick the closest standard value)	(8.2nF) **10nF**
R3	Snubber Resistor (noninductive)	$R3 = \dfrac{1}{16 \cdot \pi \cdot f_S \cdot C4}$ (pick the closest standard value)	(39.8Ω) **39Ω**
$P_{R4,MAX}$	Current Sense Resistor Power Dissipation	$P_{R4,MAX} = P_{CH,MAX} \cdot 0.015$ assume 1.5% of full output power	0.185W
R4	Current Sense Resistor (RS) (noninductive)	$R4 \leq \dfrac{0.35}{I_{L1,PEAK}}$ AND $R4 \leq \dfrac{P_{R4,MAX}}{I_{BULK}^2}$ (pick the next lower standard value)	(291mΩ) **270mΩ** (RCD type: RSF1B)
F1	Output Fuse Rating (fast acting type)	$I_{F1} = 1.25 \cdot I_{BULK}$ (pick the next higher standard value)	(1.0A) **1A**

Table 3.   Buck Converter Power Stage Components Design Sheet

Controller Design

The controller design is described in Table 4. Instructions are organized by the functional blocks of the circuit. This procedure is similar to the one explained in the power stage design. All the equations use parameters calculated or entered in the previous three tables or the preceding lines of Table 4.

Auxiliary Power Supply

The purpose of this circuit is to provide a stabilized voltage for the gate drive IC and for the UC3909 controller circuits. The auxiliary voltage has to be higher than 7.8V, the undervoltage lockout of the UC3909. Furthermore, the auxiliary voltage has to be suitable to drive the gate of the MOSFET switch directly, limiting the voltage level below 18V. The auxiliary voltage of the demonstration circuit is approximately 14.5V, to satisfy both requirements with appropriate margins.

The circuit configuration shown in Figure 4 assumes that the minimum input voltage is higher than the auxiliary voltage. In this case, R1 biases D3 to the zener voltage, and provide the base current to Q3. The auxiliary voltage will be equal to the zener voltage minus the base emitter voltage of Q3. The advantage of this solution is that the

controller supply current flowing through Q3, is independent from the input voltage.

For completeness, it should be mentioned that there are other solutions to power the controller section of the battery charger. The actual solution has to take into account the operating input voltage range, the selected gate drive technique and the type of semiconductor used in place of Q1. For example, using a P-channel MOSFET transistor will require a different gate drive technique but will allow the user to omit the auxiliary supply and to power up the UC3909 directly from the input voltage. Note that even in this case auxiliary power supply might be necessary if the maximum input voltage exceeds the VCC rating of the controller.

MOSFET Gate Drive

The gate drive circuit is based on the IR2125, High Voltage High Side Gate Driver integrated circuit from International Rectifier. The different considerations for designing the circuit are outlined in the IR2125 datasheet, [7], and are used in the component selection. The given part values are applicable for switching frequencies above 10kHz and limited below approximately 150kHz. Using the IR2125 is possible for input voltages below 500V due to the voltage rating of the device.

There is one design aspect regarding the gate drive circuit which needs to be clarified. The IR2125 like all other high side driver IC working with the bootstrapping principle monitors the voltage across the bootstrap capacitor to ensure sufficient voltage for turning on the MOSFET transistor. The first pulse appears at the gate when both voltages, VCC with respect to ground and VB with respect to the VS pin are above their respective undervoltage lockout thresholds. Thus, precharging the bootstrap capacitor, C2 is imperative to get the circuit initially running. During normal operation, C2 is charged instantaneously through the conducting rectifier diode, D2. Conversely, at start-up D2 will prevent charging the bootstrap capacitor. Fortunately the problem can be solved by a large value resistor, R23 connected between the VS pin of the IR2125 and the ground of the circuit.

Differential Output Voltage Sense

The differential voltage sense block is optional. Several trade-offs will be discussed in a later chapter together with other practical considerations. Adding a simple operational amplifier and a couple of resistors provides tighter output voltage

regulation and remote sensing capability to the charger.

The design of the differential voltage sense circuit has to satisfy two conditions. The gain of the amplifier must be higher than the reciprocal value of the number of cells connected in series in the battery. This assures that the output voltage of the differential amplifier is compatible with the voltages expected by the UC3909. A second condition is given in Table 4 ensures that the inputs of the differential amplifier stage will be kept within their common mode voltage range at any possible battery voltage. The actual gain, within these two limits, can be determined by the user.

Note that the gain of the amplifier, "A", will be used in the subsequent lines of Table 4. Therefore, even if the differential amplifier stage is omitted, the value of "A" shall be made equal to 1, and used for the rest of the calculations.

Housekeeping and Battery Temperature Sensing

The oscillator frequency is set by C8 and R8, and the UC3909 datasheet contains the exact timing equations. In Table 4, the timing equation is already solved for easily available capacitor values and for the most common frequency range. First the user selects the appropriate capacitor value based on the switching frequency defined in Table 2. Then the value of R8 is calculated, since resistor values are available in much finer steps than those of the capacitors.

In the demonstration circuit the battery temperature variation is simulated by the RP1 potentiometer. For actual temperature compensation, it shall be substituted by a L1005-5744-103-D1 type thermistor from Keystone Carbon Co. [11] or equivalent. Since the resistance of the thermistor should represent the battery temperature, it is usually mounted on or in the vicinity of the battery. To facilitate this, a two pin header, P4 is provided for convenient connection of the temperature sensor.

Current Limitation

Four resistors R9, R10, R11, and R12 program the three critical current levels, as defined in Table 1. A battery charger operates in current limited mode during trickle and bulk charge. The corresponding two current levels are the trickle current, $I_{TRICKLE}$ and the bulk charge current, I_{BULK}. A third distinct

current level is the taper current threshold, I_{OCT} where the IC will switch from over-charge to float charge regime.

The accuracy of the different current levels depends on component tolerances and on some of the parameters of the control IC. Tolerances of the external resistors can be controlled by the appropriate part selection but the internal offsets and tolerances of the UC3909 are out of hand for the designer. The largest error term inside the IC is the offset of the current sense amplifier. Its effect is especially significant in trickle charge mode and at low current levels when the measured current signal is in the same order of magnitude than the input offset of the operational amplifier. For that reason, the initial accuracy of the trickle charge current limit can be in the neighborhood of $\pm 30\%$. As the output current increases the accuracy improves rapidly and it is around $\pm 5\%$ at full current assuming 1% resistor tolerances.

Fortunately, in the battery charger application, only the bulk charge current has to be controlled precisely. The tolerances of the other two current values might influence the transitions between the charge regimes but do not represent a danger to the battery.

Setting The Output Voltages

The deep discharge threshold or cutoff voltage, over-charge voltage and float voltage are defined by the resistor network of R15, R16, R17, and R18, connected to the feedback pin of the UC3909. There are two different setup possibilities depending on whether the differential voltage sense circuit is used or omitted. With differential sensing, the calculated value of R15 resistor is placed in the position marked R15A, using the signal of the output of the operational amplifier, U4, for voltage regulation. In case of direct sensing of the output, the position R15B must be used instead. In order to provide tight tolerances of the three voltage levels, using 1% resistors is recommended.

Closing The Current Loop

"Closing the loop" is a frightening topic for many power supply designers. The detailed analysis of how to implement optimum loop compensation of the average current mode controller is beyond the scope of this Application Note. Nevertheless some excellent reference materials and design guide are

listed in the Reference section of this paper [3], [4] and [5]. These articles cover not only the design criteria of the average current control loop used in the UC3909, but also explain the critical issues related to closing the voltage loop of the controller.

Using the procedure outlined in [3], closed form equations can be derived for all feedback components and they are given in Table 4.

Voltage Loop Compensation

The voltage loop of the demonstration circuit is compensated very conservatively for stability under wide operating conditions by introducing a dominant, low frequency pole to the system. The voltage loop crossover frequency is designed to be around 1kHz, which will result in a quite slow response to fast output voltage variations. However, the circuit performance is still acceptable since battery charging does not impose severe transient requirements on the power supply.

Note, that the equations given in Table 4 are suitable to implement stable voltage loop compensation but far from achieving the maximum bandwidth or best transient behavior.

Charge State Decoder

The battery charger progresses through four different operating modes which are related to the status of the charging process and to the replaced capacity of the battery. This information can be further processed to reveal vital information about the condition of the battery, to estimate the remaining charge time, and possibly to record the history of the battery. The UC3909 can signal the actual charge state in binary coded form on the STAT0 and STAT1 outputs. A truth table for decoding the status bits is given in the datasheet.

For the users convenience, a simple charge state decoder is implemented in the demonstration circuit. The decoding function is performed by an inexpensive integrated circuit, U3. According to the STAT0 and STAT1 outputs of the UC3909, one of its outputs are activated, which will cause one of the four transistors of Q4 - Q7, and respective light emitting diodes to turn on. Each LED corresponds to one of the four charge states as marked on the printed circuit board. The resistors R6 and R5 are intended to set the LED currents and to reduce the voltage across the collector and the emitter terminals of the transistors.

Parameter	Description	Definition	Value/Part#
Controller Part Values			
C6, C7, C13, C14, C15, C16,C17	Bypass Capacitors	X7R monolithic ceramic capacitors. Minimum voltage rating 25V.	**100nF/63V**
Auxiliary Power Supply			
D3	Auxiliary Voltage Stabilizer	**$V_Z = 15V$;** zener diode; 1W / 5%	**1N4744A**
V_{CEO} (Q3)	Collector Emitter Breakdown Voltage	$V_{CEO} = 1.5 \cdot \left(V_{IN,MAX} - V_Z \right)$ (select the next higher standard value)	(22.5V) 30V
Q3	Auxiliary Power Bypass	Select general purpose NPN transistor.	**2N3904**
R1	Zener Bias Resistor	$R1 = \dfrac{V_{IN,MIN} - V_Z}{2 \cdot 10^{-3}}$	**1.5kΩ**
P_{R1}	Zener Bias Resistor Power Dissipation	$P_{R1} = \dfrac{\left(V_{IN,MAX} - V_Z \right)^2}{R1}$	0.15W
C1	Auxiliary Power Storage Capacitor	Aluminum electrolytic capacitor. Minimum voltage rating 25V.	**82µF/25V**
Gate Drive			
U2	International Rectifier	High Voltage High Side MOS Gate Driver	**IR2125**
C2	Bootstrap Capacitor	Stacked metallized film capacitor. Minimum voltage rating 25V.	**0.15µF/50V**
D4, D5	Switching Signal Diodes	Select high speed signal switching diodes.	**1N4148**
Q2	Gate Drive Inverter	Select small signal MOSFET transistor.	**2N7000**
R2	Gate Resistor for Q1		**4.7Ω**
R21, R22	Gate Drive Pull Up Resistors		**1kΩ**
R23	Bootstrap Precharger		**1kΩ**
R30	Gate Pull Down Resistor		**10kΩ**
Differential Voltage Sense - Optional			
U4	National Semiconductor	Dual Single Supply Operational Amplifier	**LM358N**
$I_{FB,MAX}$	Maximum Current Through Feedback Resistors		150µA
R24, R27	Voltage Sense Resistors	$R24 = R27 = \dfrac{V_{BAT}}{I_{FB,MAX}}$	**91kΩ**
R28, R29	Voltage Sense Resistors	$R28 = R29 = 0.001 \cdot R24$	**91Ω**
R25, R26	Voltage Sense Divider	$R25 = R26 = A \cdot R24$; where A must be $\dfrac{1}{NC} < A < \dfrac{V_Z - 3}{V_{BAT,MAX}}$	**30kΩ**
A	Gain Of Voltage Sense Amplifier	$A = \dfrac{R25}{R24 + R28}$; A=1 if amplifier is omitted.	0.3297
Charger Control Section - IC Setup - Housekeeping And Temperature Sensing			
U1	Unitrode	Switchmode Lead-Acid Battery Charger IC	**UC3909N**
C8	Timing Capacitor, CT	$f_S <$ 25 kHz 5.6nF 25 kHz $< f_S <$ 50 kHz 3.3nF 50 kHz $< f_S <$ 110 kHz 1.5nF 110 kHz $< f_S <$ 220 kHz 680pF	**1.5nF**
R8	RSET Oscillator	$R8 = \dfrac{1}{1.2 \cdot C8 \cdot f_S}$	**11kΩ**

Parameter	Description	Definition	Value/Part#
R7	Reference Resistor For The Thermistor Linearizer	Select 1%, low temperature coefficient type.	**10kΩ**
RP1	Thermistor Emulation Potentiometer	Select 10 turns potentiometer for fine resolution. (Set initial value to 10kΩ before putting it in.)	**50kΩ**
Charger Control Section - IC Setup - Current Levels			
R9	OVCTAP Set Resistor (ROVC2)	Noncritical; use:	**100kΩ**
R10	OVCTAP Set Resistor (ROVC1)	$R10 = 1.8518 \cdot I_{OCT} \cdot R4 \cdot R9$	**10kΩ**
R11	Trickle Current Limit Set Resistor (RG1)	$R11 = 43.4783 \cdot I_{TRICKLE} \cdot R4 \cdot R8$	**2.7kΩ**
R12	Bulk Current Limit Set Resistor (RG2)	$R12 = \dfrac{0.54 \cdot R11}{I_{BULK} \cdot R4}$	**6.8kΩ**
Charger Control Section - IC Setup - Voltage Levels			
R15	Battery Voltage Divider (RS1) ±1% recommended	$R15 = \dfrac{V_{C,MAX}}{I_{FB,MAX}} \cdot \dfrac{V_{C,MIN} \cdot A \cdot NC - 2.3}{V_{C,MIN}}$	**11kΩ**
R16	Battery Voltage Divider (RS2) ±1% recommended	$R16 = \dfrac{2.3}{I_{FB,MAX}} \cdot \dfrac{V_{C,MAX} - V_{C,MIN}}{V_{C,MIN}}$	**6.2kΩ**
R17	Battery Voltage Divider (RS3) ±1% recommended	$R17 = \dfrac{2.3}{I_{FB,MAX}} \cdot \dfrac{V_{C,MAX} \cdot A \cdot NC - 2.3}{V_C \cdot A \cdot NC - 2.3}$	**18kΩ**
R18	Battery Voltage Float Adj. (RS4) ±1% recommended	$R18 = \dfrac{2.3}{I_{FB,MAX}} \cdot \dfrac{V_{C,MAX} \cdot A \cdot NC - 2.3}{\left(V_{C,MAX} - V_C\right) \cdot A \cdot NC}$	**130kΩ**
Charger Control Section - IC Setup - Current Error Amplifier			
R14	Current Error Amplifier Compensation Resistor	$R14 = \dfrac{0.28 \cdot f_S \cdot L1}{V_{BAT,MAX} + V_{D1F} + V_{D2F}} \cdot \dfrac{R11}{R4}$	**3.3kΩ**
C11	Current Error Amplifier Compensation Capacitor	$C11 = \dfrac{10}{2 \cdot \pi \cdot f_S \cdot R14}$	**10nF**
C12	Current Error Amplifier Compensation Capacitor	$C12 = \dfrac{1}{2 \cdot \pi \cdot f_S \cdot R14}$	**1nF**
Charger Control Section - IC Setup - Voltage Error Amplifier			
f_0	Voltage Loop Cross-Over Frequency	Dominant pole; noncritical requirements.	1kHz
R13	Voltage Error Amplifier Compensation Resistor	$R13 = \dfrac{0.625 \cdot V_{IN,MAX} \cdot (R15 + R16)}{A \cdot I_{BULK} \cdot f_S \cdot L1 \cdot V_{BAT,MAX}} \cdot$ $\sqrt{\dfrac{1 + \left(16 \cdot \pi \cdot f_0 \cdot f_S \cdot L1 \cdot C5 \cdot \dfrac{V_{BAT,MAX}}{V_{IN,MAX}}\right)^2}{1 + \left(2 \cdot \pi \cdot f_0 \cdot R_{C5,ESR} \cdot C5\right)^2}}$	**910kΩ**
C9	Voltage Error Amplifier Compensation Capacitor	$C9 = \dfrac{C5 \cdot R_{C5,ESR}}{R13}$	**33pF**
C10	Voltage Error Amplifier Compensation Capacitor	$C10 = \dfrac{8 \cdot f_S \cdot L1 \cdot C5 \cdot V_{BAT,MAX}}{R13 \cdot V_{IN,MAX}}$	**47nF**
Charge State Decoder			
U3	Motorola	Dual Binary To 1-of-4 Decoder/Demultiplexer	**MC14555BCP**
D6, D7, D8, D9	Status Indicator LED's	Quad green LED assembly.	**IDI 5640H5**

Parameter	Description	Definition	Value/Part#
Q4, Q5, Q6, Q7	LED Driver Transistors	Minimum V_{CEO} equals $V_{IN,MAX}$ value	**2N3904**
R6	LED Current Set Resistor	$R6 = \dfrac{4.3}{0.01}$ assuming 10 mA LED current.	**430Ω**
R5	Voltage Limiter of the LED Driver Transistors	$R5 = \dfrac{V_{IN,MIN} - 7}{0.01}$	**1.1kΩ**
R19, R20	Pull Up Resistors	Noncritical; use:	**10kΩ**

Table 4.   Four State Battery Charger Controller Design Sheet

PARTS LIST

The following Bill Of Material was generated from the calculated part values listed in Table 3 and 4. The part designators correspond to the Demonstration Board component positions.

C1	82μF,	25V	electrolytic
C2	0.15μF	50V	met.film / polypropylene
C3	680μF	35V	electrolytic
C4	10nF	50V	met.film / polypropylene
C5	470μF	25V	electrolytic
C6	0.1μF	50V	ceramic
C7	0.1μF	50V	ceramic
C8	1.5nF	50V	ceramic
C9	33pF	50V	ceramic
C10	47nF	50V	ceramic
C11	10nF	50V	ceramic
C12	1.0nF	50V	ceramic
C13	0.1μF	50V	ceramic
C14	0.1μF	50V	ceramic
C15	0.1μF	50V	ceramic
C16	0.1μF	50V	ceramic
C17	0.1μF	50V	ceramic
C18	1.0μF	63V	met.film / polypropylene
D1	GI750CT		100V, 6A, general
D2	MUR610CT		100V, 6A, ultrafast
D3	1N4744A		15V,1W zener
D4	1N4148		75V, 200mA, switching
D5	1N4148		75V, 200mA, switching
D6-D9	L20355		LED assembly,IDI
L1	375μH	4A	Coilcraft
Q1	IRFZ14		60V, 10A, NMOS
Q2	2N7000		60V, 500mA, NMOS
Q3	2N3904		40V, 200mA, NPN
Q4	2N3904		40V, 200mA, NPN
Q5	2N3904		40V, 200mA, NPN
Q6	2N3904		40V, 200mA, NPN
Q7	2N3904		40V, 200mA, NPN

R1	1.5kΩ	5%, 0.25W		
R2	4.7Ω	5%, 0.25W		
R3	39Ω	5%, 0.6W		metal film
R4	270mΩ	5%, 1W	RCD-RSF1B	
R5	1.1kΩ	5%, 0.25W		
R6	430Ω	5%, 0.25W		
R7	10kΩ	5%, 0.25W		
R8	11kΩ	5%, 0.25W		
R9	100kΩ	5%, 0.25W		
R10	10kΩ	5%, 0.25W		
R11	2.7kΩ	5%, 0.25W		
R12	6.8kΩ	5%, 0.25W		
R13	910kΩ	5%, 0.25W		
R14	3.3kΩ	5%, 0.25W		
R15A	11kΩ	1%, 0.25W		
R16	6.2kΩ	1%, 0.25W		
R17	18kΩ	1%, 0.25W		
R18	130kΩ	1%, 0.25W		
R19	10kΩ	5%, 0.25W		
R20	10kΩ	5%, 0.25W		
R21	1kΩ	5%, 0.25W		
R22	1kΩ	5%, 0.25W		
R23	1kΩ	5%, 0.25W		
R24	91kΩ	1%, 0.25W		
R25	30kΩ	1%, 0.25W		
R26	30kΩ	1%, 0.25W		
R27	91kΩ	1%, 0.25W		
R28	91Ω	5%, 0.25W		
R29	91Ω	5%, 0.25W		
R30	10 kΩ	5%, 0.25W		
RP1	50kΩ	0.25W	10 turns potentiometer	
U1	UC3909N		Battery Charger Controller	
U2	IR2125		High Side Driver	
U3	MC14555BCP		Binary to 1-of-4 Decoder	
U4	LM358N		Operational Amplifier	

MEASUREMENT RESULTS

Checking Out The Circuit

To safely bring the circuit into operation, the following precautions shall be exercised to prevent catastrophic failures at the first turn on. Use sockets for all integrated circuits and do not plug them in until the auxiliary power supply is checked.

All voltages given in the rest of this chapter are with respect to circuit ground unless otherwise noted.

Step 1.

Connect the input of the circuit to your DC power source. Increase the input voltage slowly up to the minimum input voltage value used in Table 2. Check the auxiliary supply voltage at the test point, TP21. The correct value should be 0.7V less than the V_Z voltage listed in Table 4, approximately 14.3V for this example. The same voltage should be measured at pin 4 of U4, pin 1 of U2 and pin 8 of U4 integrated circuits. When all voltages are correct, remove the input power.

Step 2.

Install U1, and connect the input voltage again. Measure the reference voltage of the UC3909. The correct voltage on pin 2 (TP2) is 5V. Next, check the oscillator. Measure and compare the timing capacitor and output waveforms, TP19 and TP5 respectively, to the oscillogram shown in Figure 5.
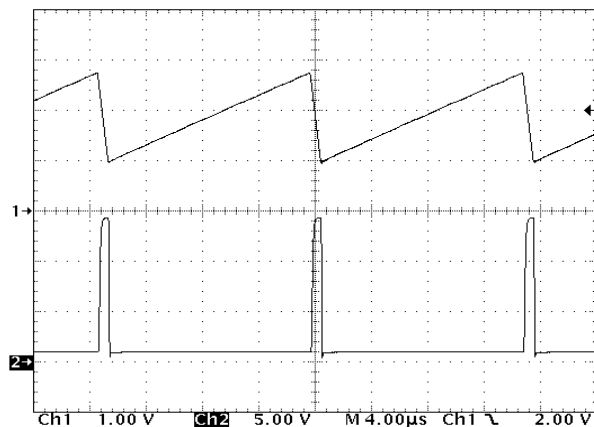
Figure 5. Trace 1: Timing Capacitor Waveform; Trace 2: OUT pin of UC3909

Compare the operating frequency to the expected value listed in Table 2. Disconnect the input voltage.

Step 3.

Populate the remaining of the IC sockets, by installing U2, U3, and U4 integrated circuits. Connect a resistive load to the output terminals. The load resistor shall be calculated as:

$$R_{LOAD} = \frac{2 \cdot V_{BAT}}{I_{OCT}}$$

Slowly raise the input voltage of the circuit while continuously monitoring the output voltage. The output voltage shall increase together with the input voltage until the output equals the float voltage, V_{BAT}. For further increases of the input voltage, the output should be regulated at the float charge voltage. If the output is not regulating, stop increasing the input voltage. Check the component values in the feedback divider, and the operating conditions of the UC3909. Convenient test points are provided in the demonstration board, for easy access to the pins of the integrated controller. The descriptions and typical voltages of the individual pins are included in the datasheet of the UC3909.

Step 4.

Once the output voltage is stabilized, check the switching waveforms of the converter. Typical waveforms of gate drive (U2/pin2), Q1 drain current, TP24, and the output inductor current, measured at full load, are shown in Figure 6.

Ch1 10.0 V   Ch2 10.0mVΩ   M 4.00µs Ch1 ⎍   3.8 V
Ch3 20.0 V   **Ch4** 10.0mVΩ
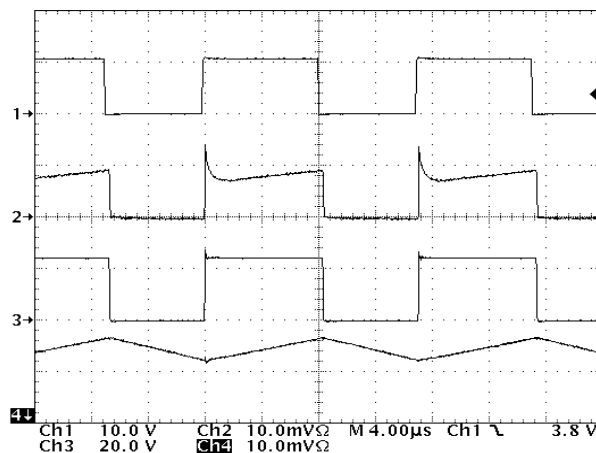
Figure 6. Switching waveforms of the converter:
Trace 1: OUT pin; Trace 2: I_{Q1} (1A/div); Trace 3: TP24;
Trace 4: I_L (0.5A/div)

Step 5.

The final test of the circuit is to check the bulk charge current limit, the float and over-charge voltage levels. The load resistor defined in step 2 ensures float mode operation of the charger. Note the

float voltage then gradually increase the load current until the charger reverts to bulk charge mode. At this point the output current should be equal to I_{BULK}. By slowly reducing the load current, the charger will sequence to the next state, over-charging. In this mode of operation the output voltage equals to $V_{BAT,MAX}$, the over-charge voltage. Verify the numbers against the values in Table 1.

Charge Characteristic

The ultimate test of the circuit is to charge a battery. The demonstration circuit has been designed to charge a 12V, 2.2Ah sealed lead-acid battery. During the charge cycle, the battery voltage and current, and the displayed operating states have been recorded. The result is shown in Figure 7.
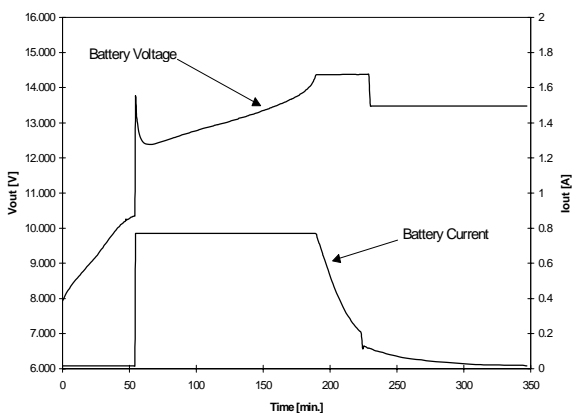

Figure 7. JC1222 Charge Characteristic

The chart shows the change of the battery voltage and charge current as a function of time and the exact values of the characteristic parameters. As can be seen, the charger started with trickle charge mode. When the battery voltage reached the cutoff voltage, the charger switched over to bulk charging. The sharp peak in the battery voltage at the switch over is caused by the high internal impedance of the battery. The majority of the battery capacity is replenished in about two hours in bulk charge mode. Bulk charge is followed by the controlled over-charge of the battery. Note that the over-charge LED is turned on before the voltage loop is satisfied because the threshold of the voltage sense comparator is intentionally set 5% below the reference of the voltage error amplifier. This way, the turn on of the over-charge LED coincides with the onset of the chemical over-charge process indicated by the gradient change in the voltage curve. The battery charging process concludes in float mode when the current tapers off to near zero.
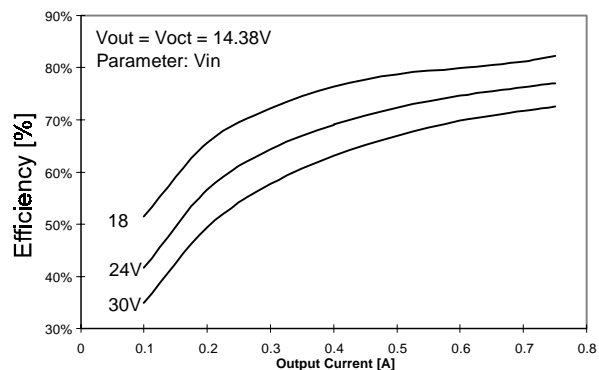
Efficiency

The efficiency of a converter is usually measured as a function of load current at a fixed output voltage and at different input voltages. While this method is really informative in DC-to-DC applications, it is very difficult to assess the efficiency of a battery charger this way. Since the load current and the output voltage of the converter vary continuously during charging, one single efficiency number carries very little information about the circuit.
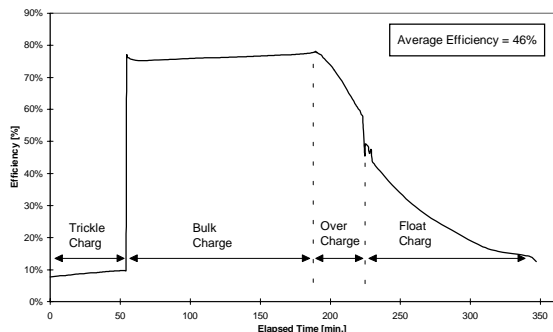
To demonstrate the effect, three different efficiency graphs are given below. The first one shows the effect of the output voltage variation on the efficiency. The second one is the traditional efficiency chart at a fixed output voltage.
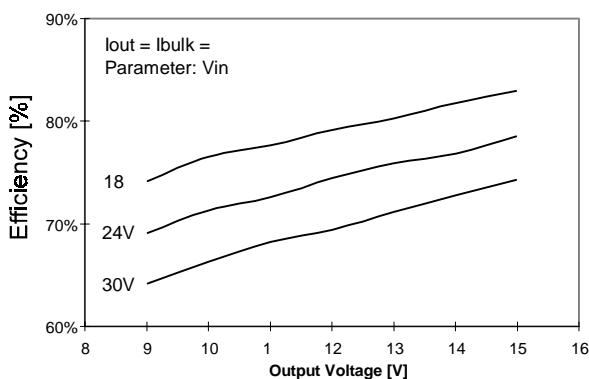
Figure 8. Efficiency vs. Output Voltage

Figure 9. Efficiency vs. Load Current

**Figure 10.** Efficiency vs. Time During Battery Charging

The third one presents the efficiencies during the entire charge cycle and the calculated average efficiency of the battery charger.

The typical efficiency of the demonstration circuit at full load with resistive load is 80%. This figure is useful for heatsink selection, and for comparison purposes.

PRACTICAL CONSIDERATIONS

Current Sense Issues

One of the most critical decisions of the design is how and where to sense the current in the converter. Using current mode control mandates sensing the current during the on-time of the switch Q1. In addition, when precise control of the output current is necessary, knowing the exact output current is inescapable. The output current of the buck converter equals the output inductor current, leaving very little choice to the designer. There are only two locations in the circuit, where the inductor current can be sensed accurately.
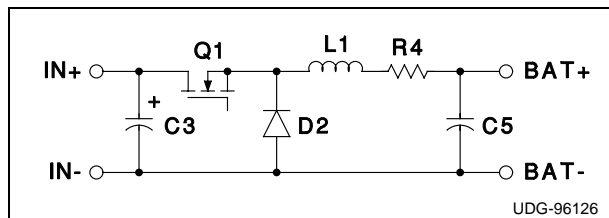
Figure 11. High side current sense technique

One possibility is the so called high side sensing, where the current sense resistor is placed in series with the output inductor as shown in Figure 11. For reliable operation it is important to put the resistor at the output capacitor side of the inductor, to avoid having a large switching component added to the inherently small current sense signal. Even with this precaution taken into account, the signal sits on top of a large common mode DC voltage

(appr. V_{BAT}) which represents a problem for the current sense amplifier.

The amplifier has a limited Common Mode Input Voltage Range and a finite Common Mode Rejection Ratio which both confine its capability and its precision when the measured signal contains a significant common mode component. To illustrate the problem, look at the demonstration circuit.

When the battery is close to its fully charged state the current signal is superimposed on a 16V DC signal. At the same time, the supply voltage of the UC3909 is approximately 14.5V. In this case the Common Mode Input Voltage Range of the current sense amplifier is exceeded and the current information is either lost or erroneous. The problem could be addressed by providing a higher supply voltage for the controller but, since VCC is also limited, the problem is just shifted to a higher voltage level.

The other difficulty, related to the finite Common Mode Rejection Ratio, arises at light load. Even if the current signal is kept within the common mode input voltage range sensing small differential voltages are difficult. For instance, the bulk current of the battery charger causes the maximum allowable 350mV voltage drop across the current sense resistor. The trickle charge current is 1% of that current providing only 3.5mV useful signal for the amplifier. Assume that the output voltage is 10V and the CMRR of the current sense circuit is 60dB. There will be two components determining the output voltage of the amplifier. The amplified current signal, 17.5mV, is added to a 10mV error signal, developed from the 10V common mode components, present at the inverting and noninverting inputs of the current sense amplifier. As demonstrated, the error caused by the common mode component is rather significant, it is in the order of 35%.

The other possibility to monitor the inductor current is in the ground return path, as it is done in the demonstration circuit. This solution eliminates both problems related to the common mode properties of the amplifier since one end of the current sense resistor is actually grounded. The disadvantage of this technique is that the input and output grounds of the charger are not the same potential any more.

The low side current sensing offers two places for grounding the controller. The GND pin of the UC3909 can be connected either to the output side of the current sense resistor, or to its node com-
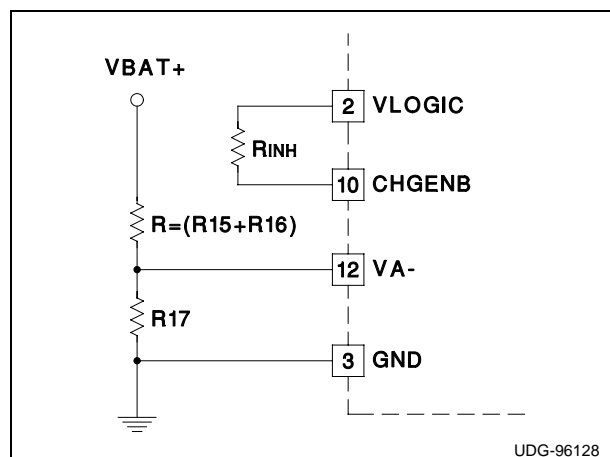
mon to the input of the buck regulator. When the IC is grounded at the output side, the output voltage is regulated perfectly. On the other hand the supply current of the UC3909 has to flow through the current sense resistor causing an error in the current measurement. The ICC of the controller has a wide tolerance which made the design of the trickle charge current very inaccurate.

Finally, the solution used in the demonstration circuit grounds the controller to the input side of the current sense resistor. It gives the best result to closely control the currents from no load to full current. The only factor influencing the accuracy of the current measurement is the input offset voltage of the current sense amplifier.

Until now, the effect of the current sense amplifier was neglected. Note that this offset is not specific to the low side sensing technique, and it would have further deteriorated the accuracy of any previously mentioned current sense method.

The current sense amplifier of the UC3909 possesses a 15mV maximum input offset voltage. This 15mV is comparable to the current signal in trickle charge mode. This explains the rather loose tolerance of the trickle charge current limit, mentioned earlier in the design chapter.

Although this approach exhibits the optimum properties to control the output current, it introduced a problem for the voltage regulation. Since the regulated voltage appears between the positive output terminal and the circuit ground, the output of the battery charger is not tightly controlled. The error is caused by the voltage drop across R4, proportional to the output current. At full current, at the beginning of the over-charge period the output voltage will be 350mV lower than the calculated over-charge voltage level, and as the current tapers off the error is diminishing. In float charge mode the output current, hence the voltage deviation from the designed value is negligible.

Differential Voltage Sense Advantages

By using the two inputs of the differential amplifier stage, the output voltage can be regulated between any two points of the output, independently from the grounding of the controller. When the two inputs are connected to the solder joints of the output connector, the effect of resistive voltage drops across the current sense resistor and on the

printed circuit board traces can be eliminated. Furthermore, the user can compensate for the external voltage drop on the wiring between the output of the charger and the battery nodes using the two remote sense connections.

Driving A P-channel MOSFET Switch

The demonstration circuit takes advantage of the lower cost and better efficiency of an N-channel MOSFET. However, using a P-channel transistor can also be accomplished easily. Figure 12 shows a possible implementation of the P-channel MOSFET switch, driven by the UC3909.

Figure 12. P-channel MOSFET Drive

The disadvantage of this technique is the relatively high power loss in the level shift circuit. The switching speed of the high side P-channel MOSFET is determined by the two series resistors connected to the output of the controller. To achieve acceptable turn-off speed the resistor values can not be increased. Therefore, the losses are especially high at elevated input voltages and at higher switching frequencies.

Skipping The Trickle Charge Mode

Depending on the battery type and the application, the trickle charge mode might not be necessary. Particularly, the new lead-acid batteries built from pure lead plates can accept full charge current from the beginning of the charge cycle. This requirement can be effortlessly accommodated by the UC3909 as shown in Figure 13.

Figure 13. Inhibiting The Trickle Charge Mode

The trickle charge mode is inhibited when the CHGENB pin is connected to the VLOGIC pin of the IC. In this case, the charger will deliver full current, independently from the initial voltage of the battery, until it sequences to over-charge.

Soft-Start

Particularly when the trickle charge mode is eliminated, soft-start of the converter might be desirable. Usually, closed loop soft-start is achieved by gradually increasing the reference voltage of the voltage error amplifier. Open loop soft-start can be implemented by clamping the output of the voltage error amplifier. None of these practices are useful in the battery charger circuit for two reasons. The first obstacle is that the temperature compensated reference of the error amplifier is not available for external manipulations. The second problem is that the battery is already connected at turn on.

Since the battery is discharged at the beginning of the charging process, the voltage error amplifier is saturated and the converter operates in current limited mode. Therefore, soft-start can be introduced only in the current control loop. In general purpose buck converters this would result in output voltage overshoot during start-up, but with the battery connected to the output, this problem does not exist. The following circuit, shown in Figure 14 can be added to provide a simple soft-start solution for the battery charger.

The output current of the buck converter will ramp up gradually to the full bulk current value according to the RC time constant in Figure 14. This solution requires extreme cautions to ensure that pre-charging of the bootstrap capacitor is accomplished well before the charging of the soft-start capacitor is complete.
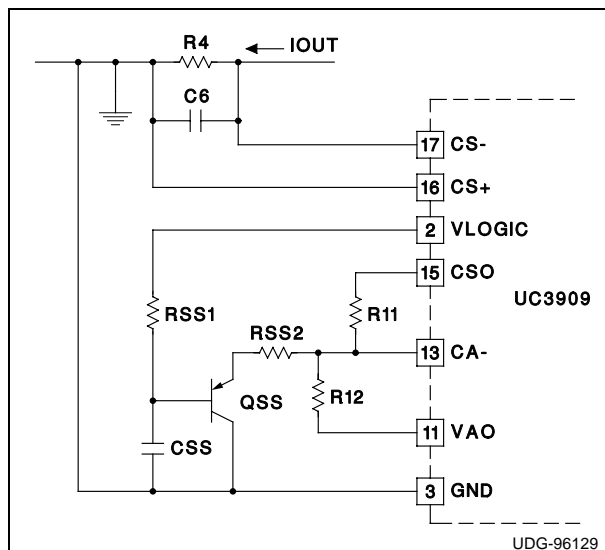
Figure 14. Soft-Start Of The UC3909

Eliminate Float Charge

The majority of the applications use the lead-acid batteries as backup power sources. In case of losing the primary power source, the system relies on the availability of the entire battery capacity. The float mode operation of the battery charger is intended to ensure that the battery is in its fully charged state during the stand by period.

As was mentioned earlier, finding the appropriate float voltage is critical to maintain 100% capacity of the battery. An easy way to avoid the problems related to float charge is to terminate the charging process upon completion of the over-charge process.
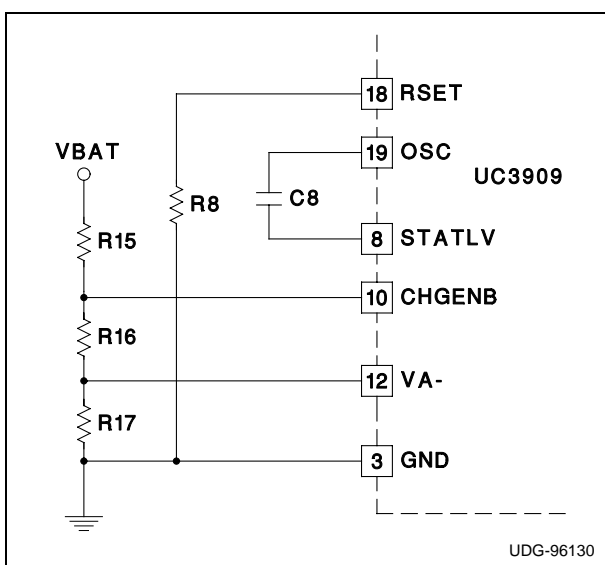

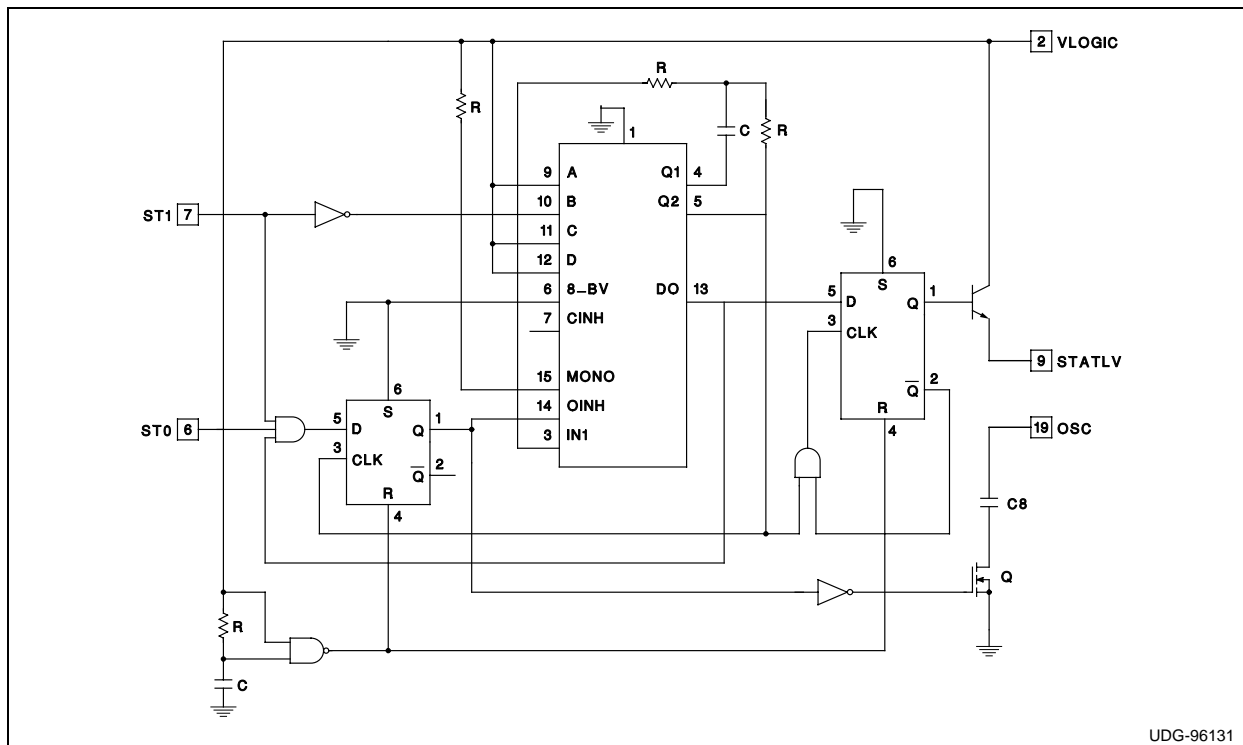
Figure 15. Disabling Float Charge State

Figure 16. Implementing The Timed Charge Method

The solution shown in Figure 15 eliminates the float mode operation by disabling the oscillator. The advantage of this approach is that the IC will recover to bulk charge mode automatically if the battery voltage drops 10% below its nominal float voltage value.

Note that there are numerous other applications which also do not require float charging the batteries. For instance, batteries in hand held tools and portable equipment are recharged quickly while the primary power source is available, but do not employ float mode operation.

Incorporating Timed Algorithms

The constant voltage charge of the lead-acid batteries necessitates combining voltage monitoring and time measurement. It requires applying constant output voltage across the battery terminals for a certain time interval. Although the UC3909 is not optimized for these algorithms, the circuit diagram in Figure 16 shows how to combine the timer with the controller.

Off-line Configurations

Very often battery chargers are operated from the AC line. Figure 17 shows line isolation with a 60Hz transformer. This technique provides a low cost,

competitive solution for low power applications. Furthermore, it can be advantageous for medium power, stationary applications because of its simplicity.
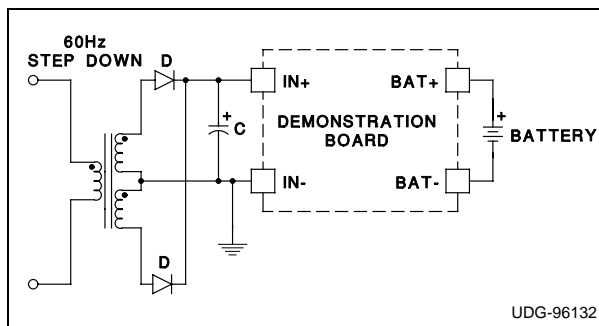
Figure 17. Isolated Off-Line Charger With 60Hz Step-Down Transformer

At higher output power, or in portable applications, the 60Hz isolation transformers become bulky. In this situation, line isolation is frequently obtained in the switchmode power stage. The forward converter, shown in Figure 18 is the isolated version of the buck topology. The components of the demonstration circuit can be easily recognized in the schematic drawing.
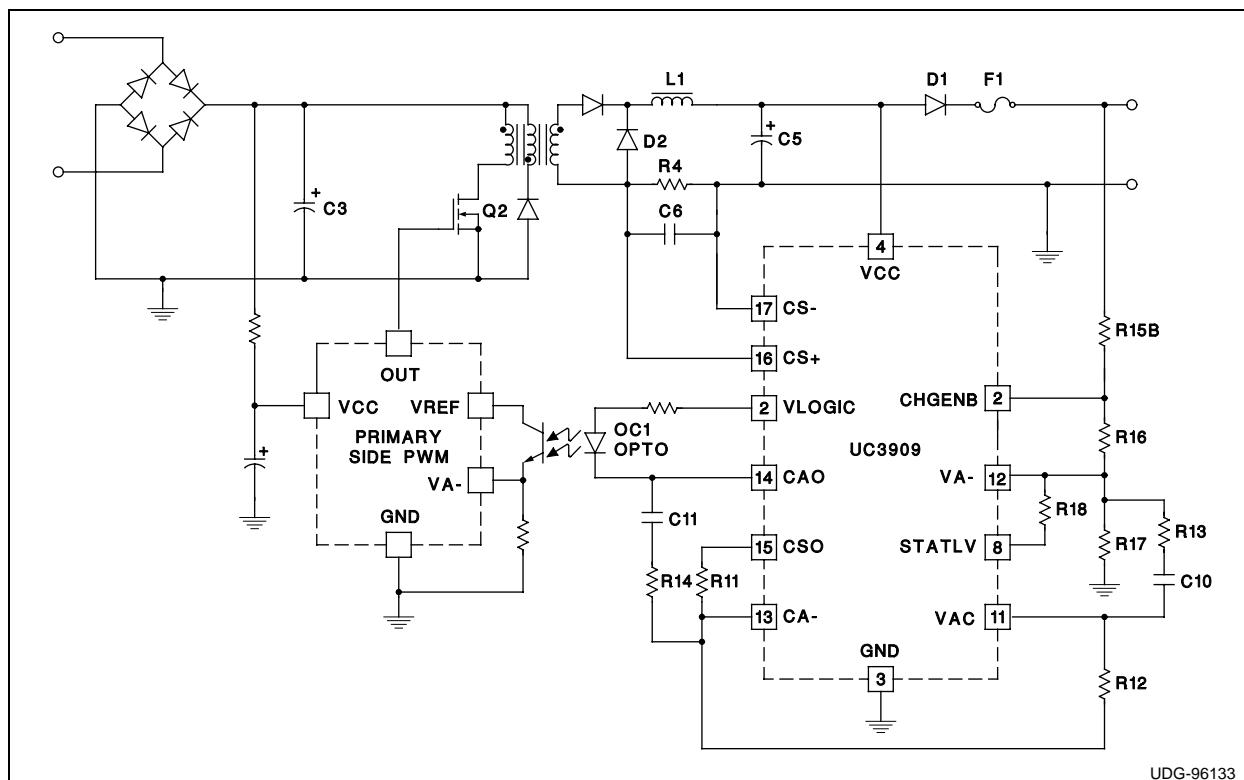
Figure 17. Forward Converter With Line Isolation

SUMMARY

This Application Note introduced the UC3909 Switchmode Lead-Acid Battery Charger controller in detail. A step-by-step design procedure of a buck converter, optimized for battery charger applications has been derived. Complete part list, and measurement results of the demonstration circuit complements the paper. Useful practical considerations are also given to help better understanding the various trade-offs involved in the battery charger design.

ADDITIONAL SUPPORT

Unitrode offers additional support to your battery charger project. The Appendix contains the Math-Cad® design file used to perform all calculations for Table 1 - 4. In addition, a printed circuit board of the fully functional battery charger circuit, useful upto 4A of continuos charge current is available for further evaluation.

For more information on the UC3909 Switchmode Lead-Acid Battery Charger controller or to order the demonstration circuit, please contact your Unitrode representative or the factory directly at (603) 424-2410.

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[3] Lloyd H. Dixon, *"Closing The Feedback Loop"*, Topic C1, SEM-700, Unitrode Power Supply Design Seminar Book

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[8] *"JC1222 Lead-Acid Battery Datasheet"*, Johnson Controls, Battery Group

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[10] *"Keystone Carbon Thermistor Catalog"* Keystone Carbon Company

APPENDIX

This MathCad file calculates the parameters and part values of the
UC3909 Switchmode Lead-Acid Battery Charger demonstration circuit.

NOTES:
- names ending to an "E" (i.e. R1E) are results of the respective calculations and they require manual entry of standard component values before continuing the calculations.

TABLE 1.

Input parameters:

$NC := 6$ — Number of cells connected in **series** within the battery.

$Cr := 2.2$ — Capacity of the battery.

$Vc := 2.275$ — Cell float voltage at 25°C.

$Vcmax := 2.43$ — Maximum cell voltage during controlled over-charge at 25°C.

$Vcmin := 1.75$ — Minimum cell voltage at full discharge on 25°C.

$It := 0$ — Trickle charge current. Enter the data from the battery datasheet or 0 for the default value (Itrickle=0.01*Cr).

$Ib := 0.8$ — Bulk charge current. Enter the data from the battery datasheet or 0 for the default value (Ibulk=0.5*Cr).

$Io := 0$ — Over-charge taper current threshold. Enter the data from the battery datasheet or 0 for the default value (Ioct=0.25*Ibulk).

$TC := -0.0039$ — Battery Temperature coefficient.

$Tmin := -10$ — Minimum operating temperature of the battery.

$Tmax := 50$ — Maximum operating temperature of the battery.

Equations: **Calculated paprameters:**

$Itrickle := if(It=0, 0.01 \cdot Cr, It)$ $Itrickle = 0.022$

$Ibulk := if(Ib=0, 0.4 \cdot Cr, Ib)$ $Ibulk = 0.8$

$Ioct := if(Io=0, 0.25 \cdot Ibulk, Io)$ $Ioct = 0.2$

$Vbat := Vc \cdot NC$ $Vbat = 13.65$

$Vbatmin := (Vcmin + (Tmax - 25) \cdot TC) \cdot NC$ $Vbatmin = 9.915$

$Vbatmax := (Vcmax + (Tmin - 25) \cdot TC) \cdot NC$ $Vbatmax = 15.399$

$Pchmax := Vbatmax \cdot Ibulk$ $Pchmax = 12.319$

TABLE 2.

Input parameters:

Vinmin := 18   Minimum input voltage of the battery charger.

Vinmax := 30   Maximum input voltage of the battery charger.

fs := 50000   Switching frequency of the converter.

Vd1f := 0.59   Forward voltage drop of D1 at Ibulk and 100°C junction
                                temperature.

Vd2f := 0.73   Forward voltage drop of D2 at Ibulk and 100°C junction
                                temperature.

Equations: **Calculated paprameters:**

$$Dmax := \frac{Vbatmax + Vd1f + Vd2f}{Vinmin + Vd2f}$$ $$Dmax = 0.893$$

$$Dmin := \frac{Vbatmin + Vd1f + Vd2f}{Vinmax + Vd2f}$$ $$Dmin = 0.366$$

TABLE 3.

Input parameters:

$trr := 35 \cdot 10^{-9}$ Reverse recovery time of D2 at Ibulk (estimate).

Irrm := 0.5   Peak reverse recovery current of D2 (estimate).

Rdson := 0.2   Channel resistance of Q1 at 25°C (the catalog data).

$Coss := 160 \cdot 10^{-12}$ Q1 drain source capacitance.

Igate := 0.8   Average gate current during turning on and off Q1.

$Qgs := 3.1 \cdot 10^{-9}$ Gate-to-source charge of Q1.

$Qgd := 5.8 \cdot 10^{-9}$ Gate-to-drain charge of Q1.

Equations: **Calculated paprameters:**

VrmmD1 := 1.5·Vbatmax   VrmmD1 = 23.099

IminD1 := 2·Ibulk   IminD1 = 1.6

Pd1 := Ibulk·Vd1f   Pd1 = 0.472

VrmmD2 := 1.5·Vinmax   VrmmD2 = 45

IminD2 := 2·Ibulk   IminD2 = 1.6

$Pd2 := Ibulk \cdot (1 - Dmin) \cdot Vd2f + 0.25 \cdot Irrm \cdot Vinmax \cdot trr \cdot fs$ $\qquad$ $Pd2 = 0.377$

$VdssQ1 := 1.5 \cdot Vinmax$ $\qquad$ $VdssQ1 = 45$

$Idmin := 4 \cdot Ibulk$ $\qquad$ $Idmin = 3.2$

$tonoff := \dfrac{Qgs + Qgd}{Igate}$ $\qquad$ $tonoff = 1.113 \cdot 10^{-8}$

$Pq1 := (Ibulk)^2 \cdot Dmax \cdot Rdson \cdot 1.5 + 0.5 \cdot Coss \cdot (Vinmax)^2 \cdot fs + \dfrac{Vinmax \cdot Ibulk}{2} \cdot (2 \cdot tonoff + trr) \cdot fs$

$\qquad Pq1 = 0.209$

$Phs := Pd1 + Pd2 + Pq1$ $\qquad$ $Phs = 1.058$

$dImax := 0.4 \cdot Ibulk$ $\qquad$ $dImax = 0.32$

$L1E := \dfrac{Vinmax}{4 \cdot dImax \cdot fs}$ $\qquad L1E = 4.687 \cdot 10^{-4}$ $\qquad L1 := 400 \cdot 10^{-6}$

$IL1peak := Ibulk + \dfrac{Vinmax}{8 \cdot L1 \cdot fs}$ $\qquad$ $IL1peak = 0.988$

$Vc3 := 1.5 \cdot Vinmax$ $\qquad$ $Vc3 = 45$

$Ic3rms := 0.5 \cdot Ibulk$ $\qquad$ $Ic3rms = 0.4$

$Vc5 := 1.5 \cdot Vbatmax$ $\qquad$ $Vc5 = 23.099$

$Ic5rms := \dfrac{Vinmax}{\sqrt{192 \cdot fs \cdot L1}}$ $\qquad$ $Ic5rms = 0.108$

$Psn := 0.015 \cdot Pchmax$ $\qquad$ $Psn = 0.185$

$Vc4 := 1.5 \cdot Vinmax$ $\qquad$ $Vc4 = 45$

$C4E := \dfrac{2 \cdot Psn}{(Vinmax)^2 \cdot fs}$ $\qquad C4E = 8.213 \cdot 10^{-9}$ $\qquad C4 := 10 \cdot 10^{-9}$

$R3E := \dfrac{1}{16 \cdot \pi \cdot fs \cdot C4}$ $\qquad R3E = 39.789$ $\qquad R3 := 39$

$Pr4max := 0.015 \cdot Pchmax$ $\qquad$ $Pr4max = 0.185$

$R4E1 := \dfrac{0.35}{IL1peak}$ $\quad R4E1 = 0.354$ $\quad R4E2 := \dfrac{Pr4max}{(Ibulk)^2}$ $\quad R4E2 = 0.289$

$R4E := if(R4E1 > R4E2, R4E2, R4E1)$ $\quad R4E = 0.289$ $\qquad R4 := 0.27$

$Pr4rated := (Ibulk)^2 \cdot R4 \cdot 5$ $\qquad$ $Pr4rated = 0.864$

$If1 := 1.25 \cdot Ibulk$ $\qquad$ $If1 = 1$

TABLE 4.

Input parameters:

$Vref := 2.3$ Internal reference voltage of the UC3909.

$Vlogic := 5$ The voltage on the VLOGIC pin of the UC3909.

$Vz := 15$ Zener voltage of D3.

$Ifbmax := 150 \cdot 10^{-6}$ Maximum current of the voltage feedback divider. This current always loads the battery.

$Ae := \dfrac{30}{91}$ Guess value of the gain (A) of the voltage sense amplifier.

$C8 := 1.5 \cdot 10^{-9}$ Timing capacitor value.

$C5 := 470 \cdot 10^{-6}$ Output capacitor value.

$Rc5esr := 65 \cdot 10^{-3}$ Equivalent series resistance of the output capacitor, C5.

$R9 := 100 \cdot 10^{3}$ Free parameter.

$f0 := 1000$ Voltage loop cross-over frequency.

Equations: **Calculated paprameters:**

$VceoQ3 := 1.5 \cdot (Vinmax - Vz)$ $VceoQ3 = 22.5$

$R1E := \dfrac{Vinmin - Vz}{0.002}$ $R1E = 1.5 \cdot 10^{3}$ $R1 := 1500$

$Pr1 := \dfrac{(Vinmax - Vz)^{2}}{R1}$ $Pr1 = 0.15$

$R24E := \dfrac{Vbat}{Ifbmax}$ $R24E = 9.1 \cdot 10^{4}$ $R24 := 91 \cdot 10^{3}$

$R28 := 0.001 \cdot R24$ $R28 = 91$

$R25E := Ae \cdot R24$ $R25E = 3 \cdot 10^{4}$ $R25 := 30 \cdot 10^{3}$

$A := \dfrac{R25}{R24 + R28}$ $A = 0.329$

$R8E := \dfrac{1}{1.2 \cdot C8 \cdot fs}$ $R8E = 1.111 \cdot 10^{4}$ $R8 := 11000$

$R10E := 1.8518 \cdot Ioct \cdot R4 \cdot R9$ $R10E = 1 \cdot 10^{4}$ $R10 := 10000$

$R11E := 43.4783 \cdot Itrickle \cdot R4 \cdot R8$ $R11E = 2.841 \cdot 10^{3}$ $R11 := 2700$

$R12E := \dfrac{0.54 \cdot R11}{Ibulk \cdot R4}$ $R12E = 6.75 \cdot 10^{3}$ $R12 := 6800$

$$R15E := Vcmax \cdot \frac{Vcmin \cdot A \cdot NC - Vref}{Ifbmax \cdot Vcmin} \qquad R15E = 1.072 \cdot 10^4 \qquad R15 := 11000$$

$$R16E := \frac{Vref}{Ifbmax} \cdot \frac{Vcmax - Vcmin}{Vcmin} \qquad R16E = 5.958 \cdot 10^3 \qquad R16 := 6200$$

$$R17E := \frac{Vref}{Ifbmax} \cdot \frac{Vcmax \cdot A \cdot NC - Vref}{Vc \cdot A \cdot NC - Vref} \qquad R17E = 1.747 \cdot 10^4 \qquad R17 := 18000$$

$$R18E := \frac{Vref}{Ifbmax} \cdot \frac{Vcmax \cdot A \cdot NC - Vref}{(Vcmax - Vc) \cdot A \cdot NC} \qquad R18E = 1.252 \cdot 10^5 \qquad R18 := 130000$$

$$R14E := \frac{0.28 \cdot fs \cdot L1}{Vbatmax + Vd1f + Vd2f} \cdot \frac{R11}{R4} \qquad R14E = 3.349 \cdot 10^3 \qquad R14 := 3300$$

$$C12E := \frac{1}{2 \cdot \pi \cdot fs \cdot R14} \qquad C12E = 9.646 \cdot 10^{-10} \qquad C12 := 1000 \cdot 10^{-12}$$

$$C11 := 10 \cdot C12 \qquad\qquad C11 = 1 \cdot 10^{-8}$$

$$R13E := \frac{0.625 \cdot Vinmax}{A \cdot Ibulk \cdot fs \cdot L1 \cdot Vbatmax} \cdot \sqrt{\frac{1 + \left(16 \cdot \pi \cdot f0 \cdot fs \cdot L1 \cdot C5 \cdot \frac{Vbatmax}{Vinmax}\right)^2}{1 + (2 \cdot \pi \cdot f0 \cdot Rc5esr \cdot C5)^2}} \cdot (R15 + R16)$$

$$R13E = 9.466 \cdot 10^5 \qquad R13 := 910 \cdot 10^3$$

$$C9E := \frac{C5 \cdot Rc5esr}{R13} \qquad C9E = 3.357 \cdot 10^{-11} \qquad C9 := 33 \cdot 10^{-12}$$

$$C10E := \frac{C5 \cdot Vbatmax}{R13 \cdot Vinmax} \cdot 8 \cdot fs \cdot L1 \qquad C10E = 4.242 \cdot 10^{-8} \qquad C10 := 47 \cdot 10^{-9}$$

$$R6E := \frac{Vlogic - 0.7}{0.01} \qquad R6E = 430 \qquad R6 := 430$$

$$R5E := \frac{Vinmin - 7}{0.01} \qquad R5E = 1.1 \cdot 10^3 \qquad R5 := 1100$$