ACHIEVING BOTH FAST RECHARGE AND LOW RISK OF OVERCHARGE IN CHARGER-CONTROLLED SYSTEMS

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Introduction

In contrast to lithium battery systems equipped with battery management systems (BMS), lead-acid and nickel cadmium batteries are unable to inform the battery charger of the ideal charging voltage. This means that the charger must rely on limited external data, such as preset charging voltage settings, battery or ambient temperature, or current demand to estimate the correct charging voltage value.

A major drawback of conventional charging is that, although it is possible to charge a lead-acid battery both quickly and safely,[1] doing both at the same time can today only be achieved under one specific set of circumstances. When any of these circumstances change, such as DC load, depth of battery discharge or differing relationship of battery AH to charger ampere output, the charging result using today's technology is always inferior. The reason is that existing methods of managing the transition between boost and float charging modes do not adapt in real time to differing charging needs.

The fastest generally accepted way to charge a battery is multi-rate boost charging. Boost charging applies a higher than normal voltage to the battery early in the charge cycle. The problem conventional chargers suffer when faced with differing conditions is that they lack a mechanism to adjust the time spent at boost voltage, versus float voltage for each particular recharge cycle. A battery that is only partially discharged, for example, would be overcharged if it were subjected to the longer period of boost voltage that would be needed to most quickly recharge a fully discharged battery. This means that designers of conventional chargers have had to choose boost-to-float mode transition points that are a compromise between fast charging performance and battery safety and longevity.

If, in contrast, the duration spent at boost voltage could be custom tailored for the differing needs of each recharge cycle, significant improvement in recharge speed and without significant increase in risk of overcharge could be realized.

This paper describes a new battery charger control system that achieves both of these goals by dynamically adjusting timing of the transition between boost and float voltage for each recharge cycle. Hereafter referred to as adaptive boost charge (ABC), this system employs more data inputs than traditional boost mode control systems. The resulting charging solution more closely approximates the charging profile that might be achieved if the conventional battery were to provide direct feedback to the charger on its condition the way lithium BMS are designed to do.

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[1] "Safely" means without violating the battery manufacturer's recommended current or voltage limits

Fast recharge is sometimes mandated and is often beneficial

Fast recharging of batteries is sometimes mandated by regulatory authorities. Battery charging performance in emergency generators and fire pumps, for example, is governed by the NEC, UL and NFPA standards. NFPA-110 and UL 1236 mandate that fully discharged batteries of Level 1 emergency generators must be fully recharged in less than 24 hours. UL 1236 includes specific tests to verify this performance.

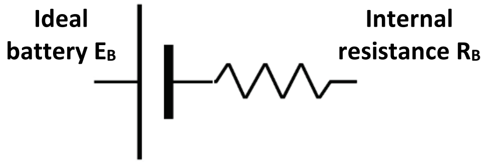
There are also practical and financial reasons to recharge some batteries quickly. Consider off-grid hybrid energy systems that typically employ renewable energy prime movers such as photovoltaic or wind, plus a large storage battery. Many of these systems are located in remote areas where refueling of the system's fossil-fueled genset (necessary to power the critical load and recharge the battery when output from the renewable energy system is unavailable) is both very expensive and inconvenient. Because the fuel efficiency of gensets degrades at partial load, the ideal battery recharge profile for lowest overall fuel consumption maximizes the time that the charger, and thus the generator, spend at maximum output, versus at partial or very low output. A battery charging profile that enables either a smaller generator, or allows the generator to spend a higher percentage of its hours operating efficiently would therefore be of economic value to these remote users.

Achieving fast battery charging is not difficult for a properly-sized constant voltage, current limited charger. Set the charger such that it operates in the boost voltage mode just long enough to mostly recharge the battery, and then switch to the float mode. The key question is, "how long in boost charge is long enough?" Too much time in boost mode could severely overcharge the battery, potentially causing thermal runaway, battery dryout, excessive water loss, excessive emission of flammable hydrogen gas and accelerated grid corrosion. Too little time in boost mode significantly extends charging time that, in the case of the remote generator above, results in inefficient use of resources and cost. In the case of some ni-cd batteries, insufficient boost charging prevents the battery from achieving its full rated capacity. The remainder of this paper discusses how a battery charger can determine and automatically adjust the time spent charging at boost voltage, versus at float voltage. The desired goal is to achieve the fastest possible recharge despite varying demands, and while minimizing risk of damaging overcharge.

Review of charging basics – "float" and "boost" charge modes

The following example helps illustrate two facts about reducing battery recharge time. The first is that cutting recharge time in half is more complex than using a charger that delivers twice as many amperes. The second is that multi-rate charging is necessary when attempting to charge quickly.

Any storage battery can be thought of as an ideal battery in series with electrical resistance. Assume in the example below that ideal battery E_B is connected in series with resistance R_B.



We will compare the battery's state of charge when it is charged with a 20A charger versus a 40A charger. We assume for purposes of this example that R_B is .001 ohms (this is an oversimplified value as the internal resistance will vary with type of cell and state-of-charge).

If we apply a charge current of **20 amps** that is voltage limited to 2.25 volts/cell, E_B (which corresponds to the state of charge of the battery) will be:

$$\mathbf{2.25 = E_B + (20^* R_B)}$$
$$\mathbf{2.25 = E_B + (20^* .001)}$$
$$\mathbf{2.25 = E_B + (.02)}$$
$$\mathbf{2.23 = E_B}$$

When charged by the 20A charger, the ideal battery sees 2.23 volts/cell.

If we apply a charge current of **40 amps** that is voltage limited to 2.25 volts/cell, E_B will be:

$$\mathbf{2.25 = E_B + (40^* R_B)}$$
$$\mathbf{2.25 = E_B + (40^* .001)}$$
$$\mathbf{2.25 = E_B + (.04)}$$
$$\mathbf{2.21 = E_B}$$

When charged by the 40A charger, the ideal battery sees 2.21 volts/cell. At this voltage the ideal battery is able to accept less current than it would at 2.23 volts/cell. In other words it will take longer to recharge the battery at 2.21 volts/cell than it would at 2.23 volts/cell.

In other words, although doubling charging current reduces charging time, it cannot cut charging time in half because the battery's resistance converts a portion of the additional charging current into heat.

This comparison shows that in order to fully exploit the current capacity of both the 20A and 40A chargers, charging voltage needs to be elevated such that it offsets resistance losses in the battery. This elevated voltage is commonly called "boost" charging.

As battery state of charge increases the ideal battery accepts decreasing current. As current diminishes less voltage is lost to heat in the battery's internal resistance. This exposes the ideal battery to increasing voltage from the constant voltage charging source[2]. If not corrected, this excess voltage would overcharge and damage the battery. To avoid this problem, charging voltage must now be reduced. This reduction could be achieved in several steps as current acceptance drops, but is typically achieved in single step, to a lower voltage charging value called "float" that allows the battery to accept just enough current after becoming charged to offset its self-discharge rate.

Charging a battery at maximum speed and with maximum safety means that the transition from boost charge voltage to float charge voltage must occur at the correct time. The correct time is the point at which the battery achieves near full charge, but before damaging overcharge occurs.

In most applications, however, the correct timing of transition from boost to float voltage is both variable and unpredictable. For example:

1. When a battery is only partially discharged the transition from boost voltage to float voltage should occur **sooner** than would be optimal if the battery were fully discharged beforehand. This is because fewer ampere-hours need to be returned to a partially discharged battery than a fully discharged one.

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[2] The term constant voltage charging means that the charger's DC voltage is maintained at a fixed value. In this example the voltage presented to the ideal battery varies not because the charger's DC voltage is varying, but because battery resistance is converting some of the charger's voltage into heat.

2. When the battery used in example (1) above is connected in parallel with a fixed DC load, and the battery is discharged to the same depth as in (1), the transition from boost voltage to float voltage should occur **later** than it did in (1). This is because the DC load is consuming some of the charger's capacity, meaning that the charger needs more time to deliver the same capacity to the battery than in (1).
3. In some systems such as uninterruptible power systems (UPS) both the load on the parallel connected DC bus (inverter) can vary from time to time, as can the battery depth of discharge (DOD). Given that these variables cannot be predicted, is entirely reasonable that sometimes the transition from boost voltage to float voltage should occur relatively soon, and sometimes it should occur relatively late. A multi-rate charger that automatically adapts to differing charging duty will deliver both faster and safer battery charging than a charger that does not adapt.

Many battery chargers today include either manual or automatic systems to manage the transition between boost and float charging modes. As shown in Table 1, however, none of them is able to optimize its performance for changing battery DOD, load, or relationship of charger to battery size:

Table 1. Summary of Existing Boost Charge Control Systems

Method	Initiation	Termination	Comments
Toggle switch	Manual	Manual	Human control is necessary to initiate and terminate boost charging. Accurate operation is impossible, as human beings rarely attend battery recharge and rarely are equipped with the necessary instrumentation.
Manually initiated timer	Manual	Automatic, based on timer setting	This is an improvement over the toggle switch that solves the problem of a human operator forgetting to return the charger to float charge mode. Accurate operation is not possible for the same reason as the toggle switch.
Automatically initiated timer	Automatic, triggered by discharge, or current limit operation or clock	Automatic, based on pre-programmed time	This is an improvement over the manual timer that automates the initiation of boost mode. It operates correctly only under one use case. All other use cases are suboptimal and cause the battery to be either overcharged after a partial discharge, or charged more slowly than optimal when there is a large connected load or after a full discharge.
Current-sensing automatic initiation and termination	Automatic, triggered by discharge or current limit operation	Automatic, based on charger output current dropping below a pre-determined threshold value	This is an improvement over the automatic timer that attempts to dynamically estimate the correct time to transition from boost to float, and back. It operates correctly only under one use case because only one use case is pre-programmed into the charger's control system. All other use cases are suboptimal for the same reasons indicated for the automatic timer.

In both of the automatic boost control systems above, the charger's designer must assume an ideal use case since the rules of operation must be coded into either charger hardware or software. The charger designer must also make policy decisions about how to deal with tradeoffs in all suboptimal use cases. As will be seen shortly, conservative, safety-conscious designers typically select time or current reversion values from boost voltage to float voltage that bias the charger to slower but safer battery charging.

In contrast to these static boost control methods, the new adaptive boost charge system automatically estimates the duration to remain in boost voltage each recharge cycle based on data about the recharge cycle that the charger collects, stores and acts on. This occurs independently each recharge cycle.

Operation of the adaptive boost charge control system

Adaptive boost charge control builds atop the current sensing automatic boost system discussed in Table 1, and operates as follows. (Steps that are new to adaptive boost charging are shown in **bold**):

1. Assume that the battery charger for this example is a constant voltage, current limited charger that includes two different voltage setpoints, one for float charging and the other for boost charging.
2. Assume that the initial operating state is a fully charged lead-acid battery connected in parallel with the charger described in Step 1. The charger is operating at the float voltage.
3. A battery discharge occurs.
4. The charger initiates the boost charging voltage if the charger senses that the now at least partially discharged battery's increased demand for current exceeds a predetermined charging current value.
5. If the battery's initial current demand after discharge exceeds the charger's rated output current, the charger operates at its current limit. This is also known as constant-current (CC) mode.
6. **At the beginning of Step 5, the battery charger starts a timer that measures duration of the CC portion of the charge cycle. Every charging cycle the charger stores in memory the duration spent in that cycle's CC mode.**
7. As the battery is recharged its acceptance of current reduces until it falls below the charger's current limit, at which point the charger transitions from CC to constant voltage (CV) mode. The charging voltage setpoint remains at the boost voltage value.
8. **When the charger transitions from the CC to CV mode the charger continues delivering its boost voltage, and starts a timer. This timer keeps the charger at boost voltage until the passage of a pre-determined ratio of the time spent in this charging cycle's CC mode.** Recall that the duration of this charge cycle's CC mode was encoded earlier in Step 6.
9. When the timer expires the charger reverts to its lower voltage float charging value, where it remains until the next battery discharge or other triggering event.

The essence of this improvement is that the time spent applying boost voltage to the battery after the CC to CV transition varies proportional[3] to the time that the charger spent in CC mode. For example:

a) In the case of a partially discharged battery with no parallel-connected DC load, adaptive boost charging would measure that CC charging was very brief. The time spent in boost mode after the CC to CV transition would therefore also be adjusted to a suitably brief interval.

b) If a heavy constant load were connected in parallel with the battery, and if DOD were identical to (a) above, the charger would measure that CC charging took relatively longer than it had in (a). The time the charger spends at boost voltage after the CC to CV transition would therefore be adjusted to a longer duration than in (a). This is the correct decision because a portion of the charger's output in this case is expended powering the DC load. Less of the charger's current is therefore available to charge the battery, so relatively more time is required to return capacity to the battery that was removed during the discharge.

Most storage battery applications experience variation in load current and depth of discharge. Because adaptive boost charge measures the duration of every CC event the system is able to shorten or lengthen the duration of time spent in boost mode after every CC to CV transition. Adaptive boost charge thus creates a unique charge profile for each charge cycle regardless of discharge duration, battery size, battery condition and connected DC load.

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[3] The proportion of time in the boost voltage setting while in the CV versus CC modes is determined by the charging system designer. The question of how to select the optimal ratio for each application is beyond the scope of this paper.

Other implementation possibilities

In Step 8 above, a timer is described as governing when the charger switches from boost voltage to float voltage. The extended boost period could also be determined by measuring the returned charge (ampere-hours) instead of time, or a combination of time and returned charge.

The timer counting down to the boost-to-float mode transition does not necessarily count down at the same rate at which it counted up during initial CC charge. System designers thus have flexibility to bias the charging system toward relatively more or less aggressive charging. Applying a minimum time limit ensures that at least a minimum amount of extended charge at boost voltage always occurs. Applying a maximum time limit addresses the risk of unlimited operation at boost voltage should a much larger than anticipated battery be matched to the charger, or if a fault in a connected load draws excessive current for long periods.

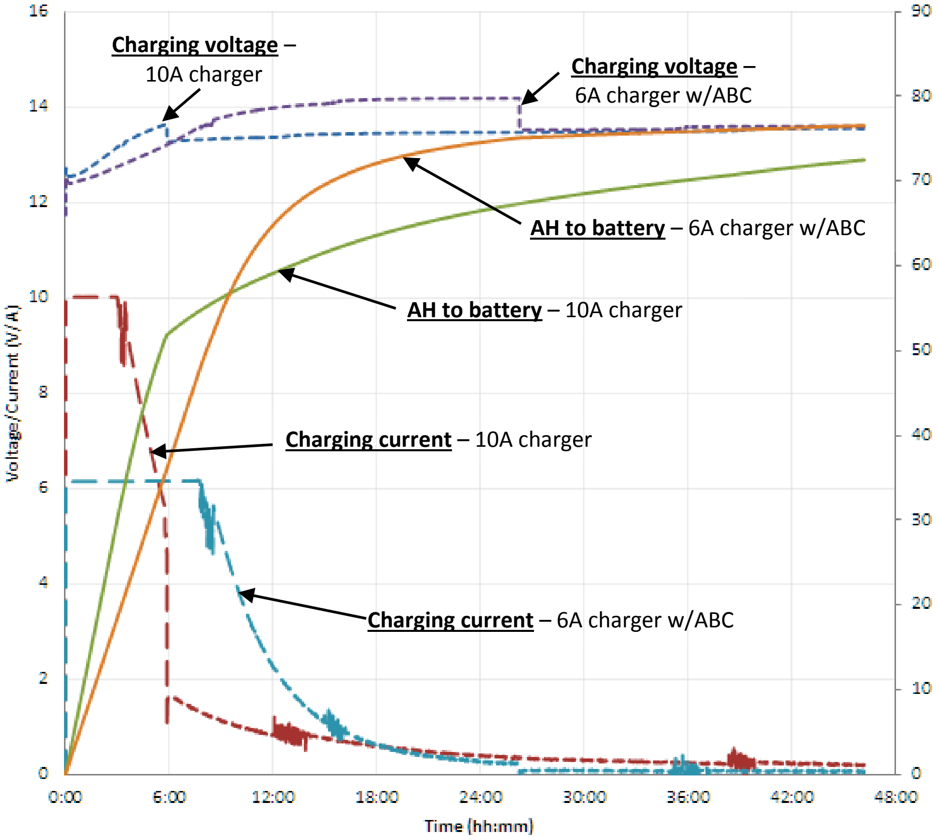
In order to facilitate comparison to existing technology the above description discusses two operating voltages, boost and float. Adaptive boost charge control could be further optimized by employing additional intermediate voltage steps that more closely align a reduction in charging voltage to diminishing internal resistance losses as the battery's charge acceptance drops.

Implementing the tasks of time measurement and computation add little to no cost if the charger is already controlled by firmware. The technology is thus well suited for packaging in a standalone charger, in the voltage regulator of a DC generator, or in the charge controller of an alternative energy system.

Results

Chart 1 compares recharge performance of a conventional current-sensing automatic boost controlled10A battery charger to an adaptive boost charge controlled 6A battery charger. Each charge cycle started with the same 75 AH flooded battery discharged to the identical manufacturer-specified fully discharged value. The X-axis shows time while the left side Y-axis shows charger output current and voltage. Total AH capacity returned to the battery is shown on the right side Y-axis. The chargers are turned on at time 0.

**Chart 1. Comparison of Recharge Performance –
6A Charger w/Adaptive Boost Charging Versus 10A with Current Controlled Automatic Boost Charging**



As expected, the 10A charger returned more capacity to the battery than the 6A charger early in the charge cycle when both chargers were operating in current limit, or CC mode. At about six hours, however, the rate at which the 10A Charger returned capacity to the battery slowed significantly, indicating that its ampere output dropped. This occurred because this particular 10A charger transitioned from at that time from boost voltage to float voltage. The 10A charger obviously made this transition prematurely, long before the battery reached full charge. This charger’s designer appears to have biased the boost-to-float voltage transition decision in favor of battery safety over fast recharge performance. We will speculate why in a moment.

Faster charging: The chart shows that the 6A adaptive boost charge-equipped charger delivered more total AH capacity to the battery than the 10A charger starting at about nine hours. At 24 hours, approximately 74 AH had been returned to the battery by the 6A charger, whereas the 10A charger had only returned around 67 AH. The 6A charger outperformed the 10A charger because it employed a more aggressive boost charging profile[4] that caused the smaller charger to operate in current limit much longer than the 10A charger. We speculate that the conservative charge settings[5] of the 10A charger were chosen to prevent potentially large connected DC loads from fooling the charger into “sticking” in boost voltage. The compromise values clearly prevented the 10A charger from delivering anywhere near its full potential charging performance in this example where there was no parallel-connected load. It is of course reasonable to expect that a 10A charger equipped with adaptive boost charge and adjusted to the same boost voltage as the 6A charger would outperform the 6A charger. In this case, however, the adaptive boost charge-equipped 6A charger handily outperformed a real-world production 10A charger.

The more aggressive charge profile employed by the 6A charger was only practical because the adaptive boost charge system is able to automatically adjust timing of the boost-to-float transition point either earlier or later than that shown. Had the battery had been only partially discharged, for example, the adaptive boost charge-equipped 6A charger would have transitioned much sooner from boost to float voltage than it did in the full discharge case shown. A charger equipped with a conventional fixed-time boost voltage termination timer, in contrast, would be incapable of automatically adapting the time spent at boost voltage as conditions changed.

More efficient use of energy can enable significant cost savings in some systems: In addition to offering faster battery recharge, an adaptive boost charge-enabled 6A charger makes more efficient use of energy during the recharge cycle than a conventionally controlled 10A charger. In some systems this advantage in efficiency has the potential to save considerable cost.

Note that nearly all battery chargers and engine-driven prime movers driving them operate at highest efficiency when more fully loaded, versus when partially loaded. This means that the most efficient use of resources (particularly fuel) is achieved by keeping the charger operating as long as possible at the boost voltage where the time spent in current limit is maximized. In other words, transition from boost voltage to float voltage at the wrong time is wasteful. Spending too much time at boost voltage would overcharge and damage the battery, requiring early replacement. Spending too little time at boost voltage wastes fuel and could require the use of a more costly, larger generator.

The chart shows that the 10A charger returned slightly more than 67% of the battery’s 75 AH capacity before transitioning to inefficient partial power operation. In contrast, the 6A charger returned nearly 100% of the battery’s capacity before transition to float voltage operation. The more aggressive charging profile enabled by adaptive boost control translates into two significant benefits for adaptive boost charge-equipped charging systems:

- A smaller capacity adaptive boost charge-enabled charger may be able to recharge a given battery faster than bigger chargers, and
- Smaller chargers enable the use of smaller generators that cost less initially and cost significantly less to fuel and maintain during their lifetime.

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[4] The more aggressive charging profile included a higher boost voltage setpoint than the 10A charger, and boost voltage control that enabled the charger to remain at the boost voltage longer than the 10A charger.

[5] The 10A charger’s boost performance was more conservative than the 6A charger’s in two ways. The first and most obvious is that the 10A charger transitioned from boost to float voltage much earlier than the 6A charger. The second is that the 10A charger was set to a lower boost charging voltage value than the 6A charger.

Summary

Fast charging of most lead-acid and ni-cd batteries requires multi-rate boost charging. Existing methods of controlling the boost-to-float charge voltage transition are compromises that deliver either inferior recharge speed or an overcharged and short-lived battery.

A new charge control system called adaptive boost charge more correctly estimates the correct time to spend at boost voltage than existing systems. Adaptive boost charge automatically adjusts the time spent at boost voltage in CV mode so that it is proportional to the time that was spent in CC mode earlier in the charge cycle. Adaptive boost charge enables the use of more aggressive charging profiles that can significantly shorten charging time without material risk of battery overcharge. Comparison testing demonstrates that an adaptive boost charge-enabled charger can recharge a lead-acid battery faster than higher current chargers employing conventional boost control methods. An adaptive boost charge-equipped charger makes more efficient use of energy and generator resources than chargers employing conventional boost control methods.

References

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DYNAMIC DEMAND-BASED AUTOMATIC BOOST CHARGE WITH TIME LIMIT