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A new pulse charging methodology for lead acid batteries

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Lead acid battery cells have low energy density and relatively low life-cycle, yet because of their cost effectiveness they are still considered the preferred choice by many electric vehicle (EV) developers and are likely to continue to be so for the next 5-10 years. One method of improving the performance of a battery powered EV is to improve the battery charging methodology since EV performance and range is largely determined by the capacity, weight and charge/discharge characteristics of the on-board batteries. This paper describes a method for fast charging lead acid batteries using current pulses of controllable magnitude and duty called 'pulse charging'. It is used together with constant voltage/current profiles to increase charge acceptance, improve the charging time, and to potentially increase the life cycle of lead acids cells.

Keywords:Battery charging - pulse charging - lead acid batteries

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1. Introduction

Lead acid batteries are one of the oldest electro-chemical storage cells. Since their discovery by Plante in 1859 their energy density, charge and discharge characteristics have been improved greatly but the basic cell elements are still the same. They are available in a variety of sizes from 1 to over 1000 Ampere-hours (battery capacity) and are almost always the least expensive storage battery for any application [1]. There are three common types available, namely; flooded, absorbed glass mat and gell, where the latter two are generally termed sealed or valve regulated lead acid (VRLA). Lead acid batteries are used extensively for energy storage, emergency power as well as for engine starting, vehicle lighting and engine ignition. Because of their cost and reliability, lead acid batteries (and VRLA in particular) are still considered to be the dominant storage battery in the near to medium term [2] especially in the EV industry where battery technology is undergoing considerable development. Yet despite this, lead acid batteries still exhibit low energy density, require high maintenance, and are slow to charge.

To be competitive with internal combustion engine vehicles, today's EVs require a safe energy source that ideally has high energy capacity, high power to weight ratio, good service life and low cost. Yet in practice they remain limited by their primary energy storage resulting in significant compromises in EV design, between total weight, performance and range. Small gains in any of these areas can improve the performance and viability of the total vehicle.

In this work, we are concerned with developing an appropriate battery charger and charging strategy that can speed up the charging of partially discharged VRLA batteries without adding significant cost or weight. Such a battery charger, if carried on-board the vehicle, would encourage opportunity charging throughout the day and enable improved optimisation of the battery on-board weight in newly designed EVs. In principle, this work should be equally applicable to flooded lead acid batteries.

To date, the most prominent and well-understood method for charging lead acid batteries is the constant current / constant voltage profile. This is a two step charging system where a battery is initially charged with a constant current until the terminal voltage reaches a threshold usually between 13.5 and 14.7 volts. After that, a constant voltage is applied as shown in figure 1, until the current tails off to a constant trickle indicating that charging has finished.

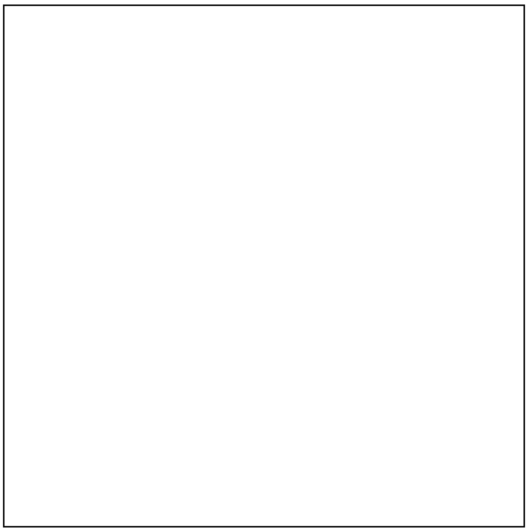


FIGURE 1: Conventional lead acid charging method using a constant current, constant voltage charger.

This charging method is easy to implement and the accuracy of the current and/or voltage regulation is sometimes compromised in order to reduce the cost of the charger. A low cost charger may consist solely of a transformer and full-bridge rectifier, and in the cheapest of these the output is often determined by the mains voltage and the turns ratio of the transformer. Usually such a circuit has no output filter so that during float charge operation the 100Hz AC ripple can produce micro-cycling of the battery consisting of small charge/discharge cycles which are increasingly detrimental over time. In more advanced low-cost models, an output voltage regulator with adjustable current limit is added, however if the limit set by the operator is too high this maybe detrimental to the battery as little or no battery monitoring is undertaken. Such chargers form the bulk of available chargers on the market.

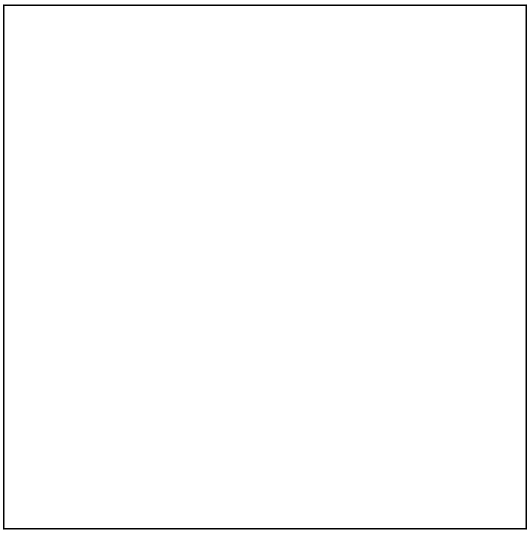


FIGURE 2: Lead acid cell charge efficiency as a function of depth of discharge.

Although constant current/constant voltage is the most widespread method used, it is far from ideal as it is inefficient, prone to gassing of the battery cells, and slow because it does not take into account the state of charge of the battery. Figure 2 shows the typical charging efficiency as a function of depth of discharge (DOD), which is a measure of how 'flat' a battery is [3]. As a battery becomes more charged (DOD decreasing) the efficiency drops rapidly as the charge acceptance of the battery deteriorates.

An ideal fast charger improves both charge acceptance and charging efficiency without detrimentally affecting the battery life. Such a charger should also operate on any lead acid cell without further complicating battery construction. Recently a new charging strategy for lead acid batteries called ‘Pulse Charging’ has been proposed [4] with the potential to provide many of these desirable characteristics, but at the time of this work this has only been tested on small specifically designed batteries. Similar pulsing strategies are known to improve charge acceptance in other battery technologies such as Nickel Cadmium, and have been commercially available for many years.

This paper improves on the work described in [4]. It begins by introducing the basic chemistry of the lead acid cell, describes conventional charging techniques and their limitations. The invariant pulse charging strategy proposed in [4] is evaluated but shown to be battery dependent. This work then describes an improved pulse charging strategy, which provides many of the features desired by fast chargers with minimal battery dependence.

2. Pulse charging of lead acid batteries

2.1 Lead acid chemistry

The chemical process of a lead acid battery consists of two electrodes - the negative electrode made of metallic lead (Pb), and the positive lead-oxide (PbO_2) electrode, immersed in a sulphuric acid solution (H_2SO_4) as shown in Figure 3.

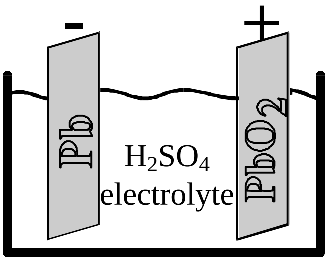


FIGURE 3: Basic lead acid cell.

On discharge both the electrodes build up lead sulphate $PbS0_4$(s) and the electrolyte is converted to H_2O, whilst the opposite occurs during charging [1]. At the negative electrode this process can be described by the following well known chemical equations:

$$\begin{aligned} Pb &\Leftrightarrow Pb^{2+} + 2e \\ Pb^{2+} + SO_4^{2-} &\Leftrightarrow PbSO_4 \end{aligned} \tag{1}$$

and similarly at the positive electrode we can write:

$$\begin{aligned} PbO_2 + 4H^+ + 2e &\Leftrightarrow Pb^{2+} + H_2O \\ Pb^{2+} + SO_4^{2-} &\Leftrightarrow PbSO_4 \end{aligned} \tag{2}$$

Thus the overall reaction can be described as:

$$Pb + PbO_2 + 2H_2SO_4 \Leftrightarrow 2PbSO_4 + H_2O \tag{3}$$

As the cell approaches full charge and the majority of the $PbSO_4$ has been converted to Pb and PbO_2, the charging cell voltage becomes greater than some critical point called the ‘gassing voltage’. At this point the overcharge reaction begins in addition to the normal charge reactions, resulting in the production of hydrogen and oxygen gas.

$$H_2O \Rightarrow H_2 + \tfrac{1}{2}O_2 \tag{4}$$

Excessive production of battery gasses is undesirable as it results in wasted energy and a substantial increase in charging time. At the same time, if the gas is not properly vented it will collect and has explosive potential, particularly in environments where electrical sparks are possible. In VRLA batteries, this problem is minimised as these gases recombine at elevated pressure, however excessive gassing as a result of poor charging forces the protective valve to vent.

2.2 Invariant pulse charging

Research overseas has shown that the hydrogen and oxygen gas development in a battery is not immediate but has a time constant relating to the state of charge of the battery [5]. Therefore if an applied current pulse is short enough, most of the current will be consumed by the charge reaction rather than producing hydrogen gas. This is the principle of pulse charging - applying relatively large currents into a battery at periodic intervals with a defined pulse width to reduce or avoid gassing and thus increase charge acceptance and efficiency. An additional advantage is that this principle can even be applied to almost fully charged batteries.

Other preliminary research [4] has shown that pulse charging produces significant reductions in charging time and an increase of cycle life. Here the authors investigated pulsing specifically designed batteries with an invariant current pulse as shown in Figure 4. When applied to the specific battery under test and compared to conventional charging, they were able to show improvements in charging time of an order of magnitude (i.e. from ten hours to one hour in small batteries) and improvements in battery life by three to four times. An added bonus was the ability to recover the capacity of exhausted or cycled cells. Initially this same approach is used in this work, but applied to more general lead acid batteries to determine the usefulness of this charging strategy.

FIGURE 4: Invariant current pulse charging.

2.3 Prototype charger

To evaluate the performance and practicality of pulse charging, a prototype pulse charger was developed. The prototype consists of a micro-controlled current source which is connected to a host personal computer (PC) as shown in Figure 5. The main components are the power electronics which form a synchronous rectifier, supervisory microprocessor and the personal computer which interfaces to the user. Together it is designed to supply up to 100 amp current pulses for either charging or discharging of the lead acid cells. It is also able to provide constant charge or discharge currents but of a much lesser magnitude due to the heating of the semiconductors. To generate the current pulses, the power electronics form a synchronous rectifier shown in Figure 6.

FIGURE 5: Overview of pulse-charger.

To understand the operation of the pulse charger, the circuit can be simplified into the two states shown in Figure 7(a & b). The first {figure 7(a)} arises when switch Q1 is on (switch Q2 is off), and the second state {Figure 7(b)} occurs when Q2 is on (Q1 off). Ignoring the inductor-capacitor (LC) filter circuit on the output, with Q1 on the voltage across the inductor forces the current I_L to ramp up. Similarly when Q2 is on, I_L ramps down. The resulting average current is determined by the duty-cycle, or ratio of the times Q1 and Q2 are on, as shown in Figure 7(c) where Q1 is on longer than Q2 so that the average current increases. If Q2 were on longer than Q1 the current would then decrease. This applies to the generation of both positive and negative currents.

The control of both switches is achieved by the comparator of Figure 6 which compares the actual current through the switches to a reference current from the micro-controller and turns the appropriate switch on. To limit the rate at which the switches turn on and off, a small amount of hysteresis is added to the comparator. The hysteresis controls the frequency of switching and hence the current ripple through the inductor. This small current ripple is considered detrimental to the battery so the output LC filter is incorporated to remove approximately 90% of the current ripple when operated at the designed operating frequency of 50 kHz.

FIGURE 6: Hysteretic current controller.

(a) *(b)* *(c)*

FIGURE 7: Basic operation of controllable current source.

The current reference originates from the micro controller which also monitors the voltage, current and internal battery pressure. A personal computer is connected to the microprocessor via an isolated RS232 serial connection and runs a windows based supervisory program which is the main interface to the charger. This custom C++ program provides simple start/stop as well as more complex control of the charger via a conventional menu and tool-bar. It also changes some of the controlling parameters for any charging profile buttons using a dialogue box. The dialogue box changes all of the pulse parameters including the hysteresis level, the period, initial current magnitude, and the discharge current magnitude.

2.4 Charging performance

To evaluate the performance of the charger and the charging method proposed in [4], two 28 Ampere-hour VRLA gell lead acid batteries were acquired with approximately the same capacity. One was fitted with pressure and temperature sensors for monitoring, while the other (with slightly higher capacity) was left as supplied.

In Figure 8 a selected result of a typical charging profile on the modified battery using conventional charging techniques is shown. The charging current of 7 amps represents a typical overnight charging rate for this sized battery, and was the limit of the conventional charger supplied. As illustrated here, once the terminal voltage reaches the charging voltage (usually between 13.5-14.7volts) the charging rate is dictated by the charge acceptance of the battery and contributes to as much as 80% of the charging time. After 3 hours, 50% of capacity is returned and the rate of charge for the remaining 50% is very slow, taking in excess of 30 hours. Attempts to speed up the battery charge-rate are limited. In the constant current region either the capacity of the power source or thermal characteristics within the battery determine this limit. In the constant voltage region a larger applied voltage or an alternative constant current charge scheme only increases the production of H_2 and O_2 gassing of the battery and does little to improve the charging time. It is in the latter region where pulse charging can provide clear benefits in charge rate as described in section 3.

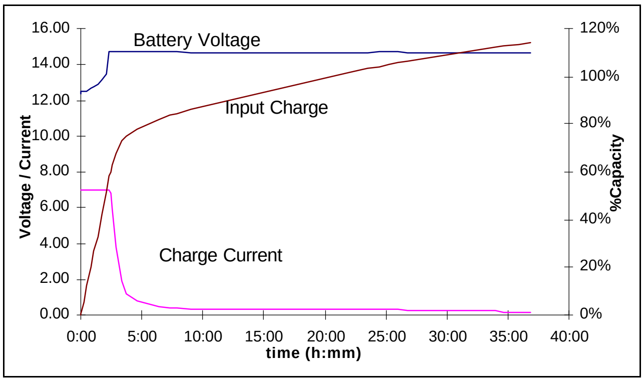


FIGURE 8: Conventional charging of lead acid battery.

Conventional constant current-constant voltage charging schemes provide little feedback information to indicate either the state of charge of the battery or battery condition. The only indication that the battery is charged is given by monitoring the current taper until it is consistently small over a one-hour period. A more accurate method of calculating the state of charge requires integrating the current with time but this requires a known starting point and does not take into account the efficiency of the battery.

This same battery was tested with the invariant current pulse of figure 4 with 28 amps peak current being applied for 200msecs, and then zero amps for 600msecs, giving an overall period of 800msecs and an average current of 7 amps for comparison with the conventional charger. These sets of results can also be compared with that expected from the work done in [4].

Figure 9 shows the input charge to the battery and the internal battery pressure of the sealed VRLA lead-acid cell. The invariant pulsing is similar to a constant current since the apparent charge capacity is strictly linear. The most important feature of figure 9 is the internal battery pressure. As the cell is charged there is a small, slowly increasing pressure of about 0.5psi. Then at 2 hours the pressure build up becomes quite rapid until the cell pressure exceeds the venting pressure of the cell and it drops suddenly as the gas is released from the vent. After 3 hours the charging was terminated since the battery began ‘hissing’ as the other cells also vented gasses. The presence of quite aggressive gassing indicates that the invariant pulse charging trialed is unsuitable since at high states of charge (SOC) the applied current pulse is too long and causes the production of the gasses.

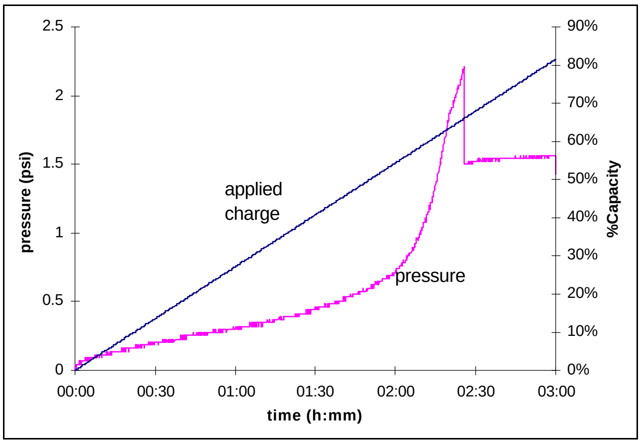


FIGURE 9: Capacity and pressure during invariant pulse charging.

By completely discharging the battery, the efficiency between the charge and discharge capacities (measured in ampere-hours) was found to be 91% which is reasonably high. An obvious advantage of the pulse width invariant method is that in just 3 hours 80% of the capacity of the battery had been restored.

Figure 10 shows the relative input charge rates between the constant current and invariant pulse techniques. As expected both strategies have similar charging rates, the slight difference resulting from limitations in the prototype charging control. As the charging time approaches 2 hours and 30 minutes, under conventional charging the charger becomes voltage limited to 14.7 volts and the current begins to decline as can be seen in the lower plot. In comparison the invariant pulse keeps charging at the same rate irrespective, indicating higher charge delivery.

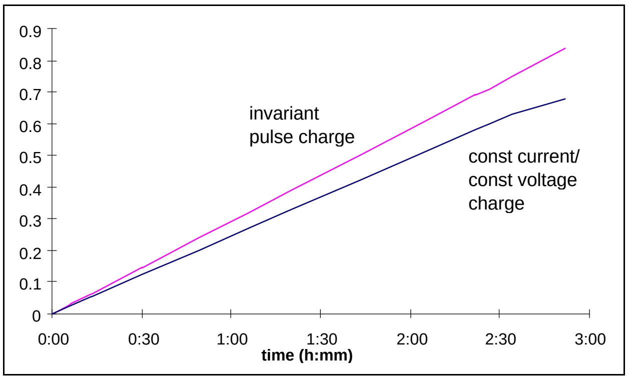


FIGURE 10: Input charge rate comparison between conventional and invariant current pulsing

At high SOC, it is obvious that the invariant current pulse is unsuitable for charging the two sealed VRLA lead acid batteries investigated because of gassing. To eliminate this problem the pulse-width must be shortened, but this is not the case at low SOC when the charge acceptance of the battery is high. Here significant improvement can be made by increasing the pulse width without fear of gassing, thereby increasing the average current and speeding up the battery charging. Clearly a better pulsing strategy is required which satisfies both of these extremes.

3. A new variable pulse charging strategy

3.1 Voltage dependent charge rate

An alternative pulse charging strategy which avoids the problems discussed above, utilises a controller that allows the average current of the pulse train to vary in a manner similar to the more conventional charging profile. This can be achieved by applying a current pulse no greater than a maximum period, but adding the ability to terminate the pulse if it appears the gassing voltage of the battery is about to be exceeded.

FIGURE 11: Variable current pulse charging.

Applying this pulse charging concept results in a charging profile similar to that shown in Figure 11. Each applied current pulse is required to be on as long as possible within a maximum period, but the battery voltage must not exceed the gassing voltage of 14.7 volts (2.45 volts per cell). This ensures that the duty of the pulse width approaches 100% at low states of charge, thereby providing maximum charge delivery while the battery is in a state to accept it. The terminal voltage of the battery is then monitored at all times so that when the peak internal voltage is determined to have exceeded the gassing voltage, the current pulse is terminated. The result is a two stage charger, with an initial constant average current which is then decreased as the battery voltage reaches a threshold, thus resembling the current profile of the constant voltage / constant current charger. However, the physical resistance of the terminals, internal grid structure and the resistance due to the chemical reaction cause the internal voltage to be lower than the terminal voltage so that some means of estimating this internal resistance must be incorporated in the feedback control [6]. The compensated or resistance free voltage once found is used to determine when to terminate each current pulse.

The two test batteries were charged with this varying pulse current scheme. Again the current magnitude was chosen to be 28 amps but to retain some pulsing, this peak current can only be applied for a maximum of 780msecs of the 800msecs period chosen. The current pulse naturally reduces as the SOC of the battery improves as the rise time of the resistance free voltage to the gassing voltage shortens.

Figure 12 shows the on-time of the current pulse and the input charge delivered to the battery. The most important feature of this graph is the high charge delivery (85% of the battery capacity) in a relatively short time. A 200 ms on time represents an average applied current of 7 A, which is reached at approximately 50% of the battery capacity in approximately 45 minutes. The last 35% is added in only two hours with the average currents tapering off to 1.75 A.

The dark band in the pulse on-time of Figure 12 corresponds to variations in this on-time as the gassing voltage detection circuitry begins to impact the current pulse width. This occurs only near the knee of the curve as the duty cycle begins to decrease.

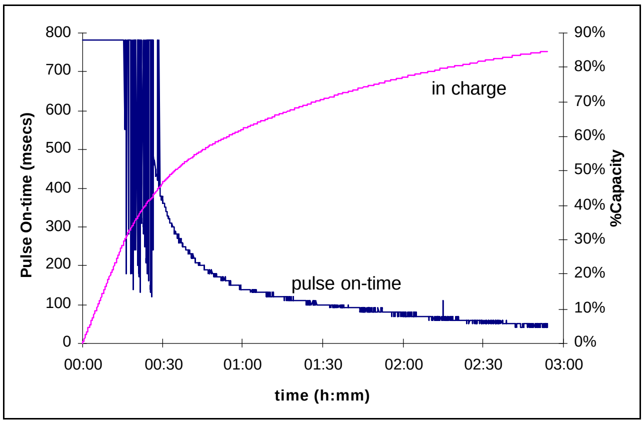


FIGURE 12: Pulse on time and capacity of variable pulse charging

Figure 13 shows the internal battery pressure. During the early charging stage with the battery in a low SOC, the pulse length is a maximum of 780 ms so that there is a rapid buildup of internal pressure within acceptable battery limits as no venting occurs. The internal pressure then drops as the pulse widths begin to reduce.

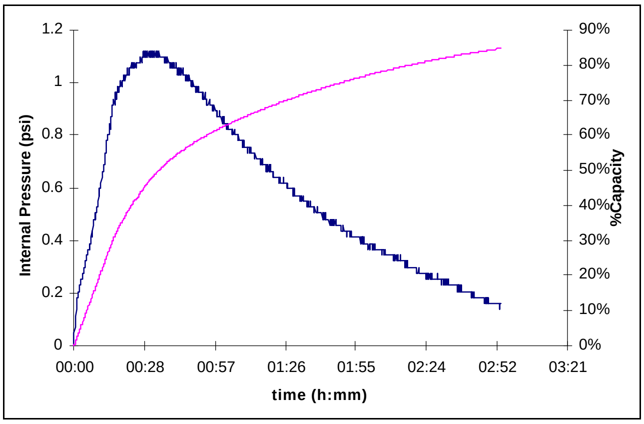


FIGURE 13: Internal battery pressure during pulse charging.

These changes in internal pressure are partially a result of internal temperature increases (from ambient (25°C) to 36°C) due to resistive power loss within the battery. Assuming ideal conditions for a gas, the change in pressure due to a change in temperature (constant volume) can be expressed as:

$$P_2 = \frac{P_1 T_2}{T_1} = \frac{101.3 \bullet (273+36)}{(273+25)} = 105.0\text{kPa} \Rightarrow \Delta P \approx 0.6\text{psi}$$

where pressure (P) is in kPa, volume (V) in m^2, temperature in K.

Assuming that at rest the absolute internal battery pressure is 101.3 kPa then a change in pressure of at least 0.6 psi is expected at elevated temperatures, and for this type of charging a large proportion (if not all) of it is due to internal heating. At higher states of charge the proposed strategy naturally reduces the average current so that internal battery losses are less. This contributes to lower internal pressures as the battery cools. The apparent lack of internal pressure at high states of charge verifies the compensated maximum voltage used for terminating the pulse and thus reduces the potential for gassing to occur.

3.2 Further improvements for charge acceptance

As the battery state of charge increases the concentration of active materials near the grids within the battery begins to decline and is one of the factors that results in lower charge acceptance. This concentration is lowest near these grids but increases as the distance from the plate increases. If a small discharge pulse is applied immediately following each charging pulse the concentration differential attempts to reverse. This reaction partially restores the concentration of active materials thereby improving the charge acceptance of the next applied current pulse. This effect can be seen in the monitored battery terminal voltage which begins to drop immediately after the positive current pulse has finished. This voltage should ideally be allowed to decrease to around 13-13.5 volts, indicating sufficient restoration of the concentration gradients surrounding the plates to ensure good charge efficiency in the next delivered pulse. A modified pulse charging strategy is therefore proposed (Figure 14) in order to investigate the effectiveness of such a strategy. Essentially this charging strategy is the same as that proposed earlier (Figure 11) except for the addition of the discharge pulse.

FIGURE 14: Variable current pulse charging with discharge.

The discharge pulse used here has a magnitude limited to 20% of the initial current, with a discharge pulse area approximately 8% of the charging area. When the battery is in a low SOC the positive pulse is on for 570msecs and this discharge pulse exists for the remainder of the period. As the battery SOC increases the controller reduces the pulse (charge and discharge) width in a similar manner to that described in the previous section while maintaining this discharge area at 8% of the charge area.

The on-time of the current pulse and the input charge to the battery is shown in Figure 15. The charging is still rapid and declines as expected when the battery voltage begins to influence the pulse width. Note that there is no erratic switching period near the knee of the pulse-on time curve which occurs when there is no added discharge pulse.

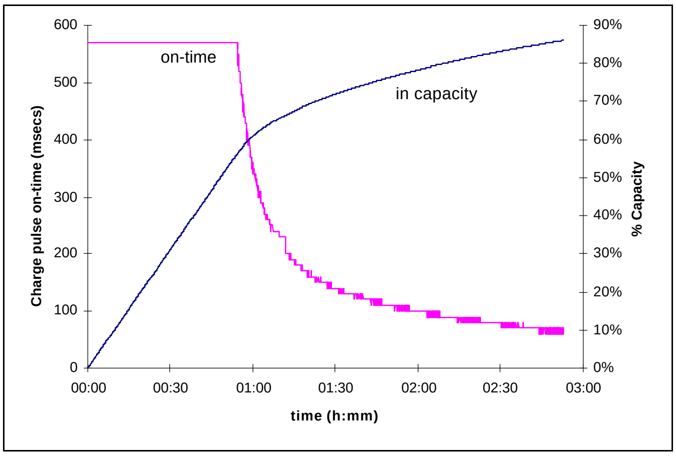


FIGURE 15: Pulse on time and capacity of variable pulse charging with discharge

More importantly, Figure 15 indicates that the charging time and hence charge acceptance has improved since the battery has reached 80% SOC as quickly as the previous pulsing technique without the discharge. This is despite the reduction in average current, since the peak current value is constant but offset by the 8% discharge area. This is verified by the improved charging efficiency of 89% but the improvement may be larger due to the error margin of the testing equipment.

Figure 16(a) illustrates the relative charging rates of the pulse charging strategies with and without the discharge pulse after approximately 50% SOC, while in Figure 16(b), these charging rates are compared with that of the conventional charging approach. In the above figures the 'constant current' charging region is not included because during this part of the charging cycle the initial charge delivery of each strategy is vastly different, being fixed by the period and duty of each. For example, in the early charging stages the additional discharge pulse reduces the charging rate by 8% making direct comparison of the pulse charging strategies more difficult.

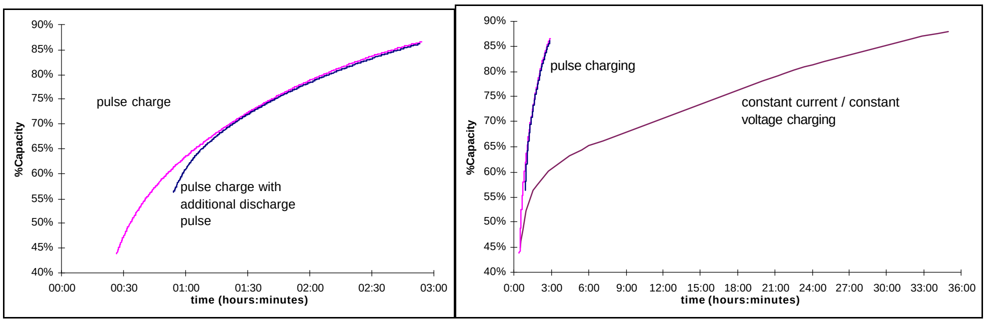
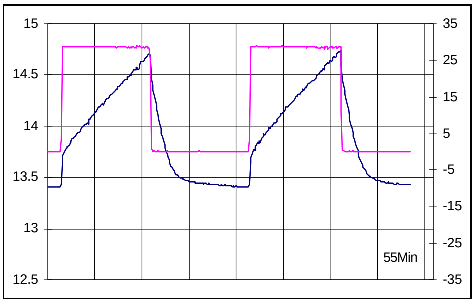


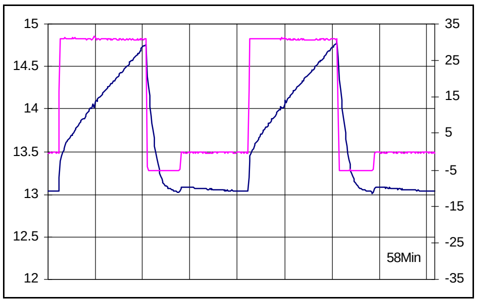
FIGURE 16: Relative charging rates.

As noted earlier what is of particular interest in Figure 16(a), is that despite an 8% lower charge rate due to the added discharge pulse this second variable pulse strategy reaches 70% state of charge in the same time, indicating improved charge acceptance. Figure 16(b) on the other hand shows the obvious improvement that pulse charging has over conventional techniques. This is because the charge acceptance within the constant voltage region of conventional chargers is severely limited as described in section 2.4.

Figure 17 illustrates the effect that adding this discharge pulse has on the monitored battery terminal voltage. As shown, by adding the discharge pulse {Figure 17(b)} the battery is bought to a state where it is ready to accept a new current pulse sooner than the initial pulse charging strategy {Figure 17(a)}. In principle this means that the next charging pulse could be reapplied sooner than the control strategy presently allows, resulting in even faster charging being achieved. Clearly, pulse charging with a fixed period will eventually reach a stage where the charging pulse is reapplied before the battery is in a state to gain the most benefit from it.



(a)



(b)

FIGURE 17: Voltage and current waveforms at approximately 55 minutes.(a) without added discharge pulse (b) with discharge pulse added (vertical scale 0.5 V/div, 20 A/div, horizontal scale 0.2 s/div).

Finally, although pulse charging significantly improves the charge time over the period where the battery has 50% to 80% SOC, the remaining 20% of charge is still relatively slow. But the improvement in charging time during the 50% to 80% region is important because this is the operating region of EV batteries, especially those requiring frequent opportunity charging. The overall improvement from 30 hours to 3 hours is consistent with overseas results, even though the pulse width is varied throughout the charging cycle as dictated by the needs of the battery.

4. Conclusions

To validate the advantages of pulse charging, a working prototype has been developed. This is a general purpose charger capable of generating large current pulses for charging or discharging the battery while a connection of a PC allows a simple interface between the user and the charger which is capable of changing the charging profiles, and storing the received data.

A simple ‘unintelligent’ invariant pulse charging approach was shown to dramatically decrease charging time but is also capable of gassing the battery and must be applied with care. In this technique specific pulse widths and/or magnitudes must be chosen carefully to fit each lead-acid battery and may need modification with battery age.

A new pulse charging approach is proposed with variable pulse width controlled by feedback resistance free battery voltage, presenting an average current to the battery that is similar to conventional charging profiles. This approach is shown to dramatically improve the charge rate outside of the constant current region (typically around 50% state of charge). In addition, it appears to eliminate gassing at these high states of charge, and does so without the need of additional sensors. A practical observation is that high currents applied during the initial part of the charging cycle cause consistent but limited temperature and pressure rises that may require monitoring (particularly for sealed VRLA lead-acid cells). If the battery is placed at elevated temperatures then higher currents than specified by the battery manufacturer should be used with care.

The inclusion of a small discharge pulse gives a slight improvement in charging efficiency without reducing the charging time, despite the initial lower average current. Both variable pulsing methods show significant improvements in charging time compared with conventional means, illustrating the potential to rapidly improve the useability of lead-acid batteries in EVs by opportunity charging.

5. Acknowledgments

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6. References

1. A J Salkind, G E Mayer, D Linden, “Handbook of batteries and fuel cells”, McGraw-Hill, Ch. 14 pg. 1, 1984
2. M J Miles, "Energy Sources for Electric Vehicles - A Review of Current Technology", Proc IPENZ Conf., Hamilton, pp 59-68, February 1993
3. M J Miles, "Torque control of cage induction machines using field acceleration", PhD Thesis, Department of Electrical and Electronic Engineering, The University of Auckland, 1994
4. L T Lam, H Ozgun, O V Lim, J A Hamilton, L H Vu, D G Vella, D A J Rand, “Pulsed-Current charging of lead-acid batteries - a possible means for overcoming premature capacity loss?”, Journal of Power Sources, Vol 53, 1995, pp 215-228
5. D K Nowak, “Gas Detection and minimisation of gas and heat production at the end of fast charging”, Journal of Power Sources, Vol 40, 1992, pp105-110
6. J J A Wilkinson, “Te Pakahiko o te Waka Hiko. Electric Vehicles: the battery block”, ME Thesis, Department of Electrical and Electronic Engineering, University of Auckland, 1996