Title: **Testing Pulsed Current Conditioning to Benefit Vehicle Battery Performance**

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Session:

(A) ~~Passenger Cars~~

(E) *Testing & Instrumentation*
code PC10

Abstract

This paper reports work done to address the question of whether pulsed power conditioning, such as employed in some battery rapid-chargers, might improve the electrochemical transformation efficiency for the electric or hybrid electric vehicle drive train. Rapid-charger literature suggest better transfer efficiency and battery life maintenance for lead-acid and other battery systems. After reviewing the literature, an experiment was conducted with two batteries from electric shuttle buses of the Chattanooga Area Rapid Transit Authority (CARTA). These batteries were alternately charged and discharged using two charger types and three discharge types, so that the degree of current "chopping" could be varied. The batteries were thermally insulated and electrical parameters measured to conduct an energy balance analysis after 24 permutations of the energy transfer methods. A transfer rate between 8 and 14 kW was used in these tests, and the 300 AH batteries were charged/discharged at approximate the C₆/6 rate (40-50 A). The paper will report on the type of recordings taken, along with limitations and difficulties encountered, and will combine test data in summary plots to show what trends could be resolved.

The conclusions regarding improved transfer efficiencies under the conditions tested were negative. Left open is the questions of benefit under conditions of higher transfer rates, or for battery life cycle improvements. Considerations for further testing under these conditions are included.

(Testing done at CARTA by the author and the Electric Transit Vehicle Institute (ETVI) under contract #MDA972-94-2-0003, Southern Coalition for Advanced Transportation (SCAT), Atlanta, GA.)

Testing Conducted

The CARTA garage is equipped with battery chargers supplied by the battery manufacturers for use with specific electric bus systems. These have fixed voltage and charging rates. There is also a prototype EPTI [12] rapid charging unit at that location which has controllable parameters to service a variety of batteries. The rapid charger is a pulsed charger using counter pulsed current during off cycles of charging (figure 1). The unit is capable of charging at 250 A and up to 400 V.

With these resources available, a hypothesis was formulated for testing. It was proposed that the rapid pulsed charger would be more efficient than the standard charger in the utilization of volt-amperes delivered to the battery. This would be due to the benefits of electrolyte conditioning by the current algorithm. For the same reason, it was proposed that a chopped discharge current would deliver battery energy to the terminals more efficiently and, further, that a higher frequency of chopped current would generally improve efficiency until the AC conductor losses dominated over gains. The improved efficiencies would be evidenced in lower battery temperature rise per kWh of energy transferred. Therefore it was proposed to tightly monitor the energy delivery to and from a battery set using the two charging methods and several discharging methods, and then demonstrate by careful measurement the corresponding difference in energy dissipated by the various methods.

Limitations on testing

It would have been desirable to test the battery at the high transfer rates afforded by the rapid charger. The standard charger, however, could not accommodate a comparable rate. In addition, the battery connection jumpers were sized for the expected average current (40-50 A) and would overheat with continuous high current application. For these reasons, a charge/discharge rate was settled on which matched the standard battery charger [13] in use by CARTA (~40 A). The current waveform for the standard charger is actually a 120 Hz. unipolar shape as seen in figure 2.

To vary the method of discharge, a controller was built to variously apply (1) a direct current to a fix resistor, (2) a square wave current at 1 Hz. to half the resistance, or (3) a square wave current at 200 Hz to half the resistance. In this way the average current would be the same in all three cases, and the test variable would be the on-off frequency of the discharge.

Batteries

The two batteries used in the test are nominally 216 V, and designed for an average current level of 50 A. The 6 hr battery capacity rating is 300 AH. There are 27 cells packaged in each of four modules, all 108 of which are wired in series. They were manufactured by KW Powersource (Chattanooga, TN) and first put into service by CARTA on December 5, 1996 (#702C, battery "B") and December 6, 1996 (#702A, battery "A"). They had been cycled (i.e., used and recharged) over the 8 month period before the August 1997 tests, a total of 117 (#702C, battery "B") and 120 (#702A, battery "A") times. Table 1 shows the mass distribution for each battery. The batteries were laid out with 5 cm (2 in.) thick polystyrene foam insulation in order to provide adiabatic and isothermal test conditions during the charging and discharging procedures. Between tests, the insulation was removed, allowing the batteries to cool to nearly the same starting temperature before the next test. While enclosed, breather tubes extended the filler cap openings above the top insulation and provided access for the immersion of individual cell thermocouples. The test setup is shown in figure 3.

Procedure

The two thermally insulated batteries were alternately charged and discharged using two charging methods and three discharging methods. A test matrix was generated, comprised of 12 charge-discharge permutations and repeated, for the 24 run sequence. Computer acquired recordings were made of the battery terminal voltages and currents, both averaged and instantaneous. Recordings were also made of 14 thermocouples arrayed in each battery. Data was acquired at one sample every 10 s, with a burst collection of 12,000 samples in 1 s at every half hour. The burst data allowed a check on actual voltage and current waveforms as the test proceeded, while the slower data

recorded the longer term patterns of energy transfer. The charged battery was discharged until the terminal voltage reached 204 V, and the discharged battery was charged until finished according to the normal charger settings (~280 V). This averaged a cycle of ~42% of the full nameplate capacity of the battery. The cooling criteria between tests was to be within 3°C of the room ambient, and that all battery cells should be within 1°C of each other.

Results

Data was collected as the operator worked through the test matrix over a 21 day period. Each run lasted between 3.5 and 5.5 hr for charging; the discharge time was consistently $3.4 \text{ hr} \pm 0.2 \text{ hr}$. Table 2 shows the average time and temperature rise for each method used. The ambient temperature over the twenty-one days varied from 21.5°C to 36.8°C, with an average of 27.7°C.

In the course of testing, the discharge controller failed four times. Each time, the IGBT switch, used for switching the discharge current at either 1 Hz or 200 Hz, was destroyed by overheating. Analysis of data afterward revealed that the IGBT gate circuit would occasionally oscillate in response to noise pickup from the pulsed charger circuit. Figure 4 shows an example of this oscillation captured on one of the burst data files. The oscillation frequency exceeds the 12 kHz sampling rate. The slow data trace of average terminal voltage reflects this event as a reduce average voltage. The extra heat of the fast switching in this manner was determined to be the cause of the failed IGBT switches. Evidence of oscillations appeared in eight of the 24 runs, but only four of these lasted long enough to evidence reduced battery voltage on the slow data traces. The noise from the pulse charger also left signatures on the thermocouple readings, which were easily filtered from the much slower temperature data, however.

The data were reduced to provide the total energy delivered to and from the batteries, and multiple temperature readings were averaged to show temperature rise detail. The purpose of the burst data, aside from waveform inspection, was to correlate the slow scan averaged signals for V and A to their actual RMS values as observed for a second at a time. Mathematically, the square wave will have an RMS value $1.414 \times$ the

average value, which is half the height of the wave. The 1 Hz and 200 Hz discharge waves should have average current values at one half of their on-state level. Since battery voltage is fairly constant, the resistor load was calculated to offer twice the current and power level when the discharge was conducting at a 50% duty cycle. The charging waveforms are more complicated; in all cases, however, the burst data allows a direct calculation from measured values. The normalized ratio values for the voltage and current waveforms observed are shown in table 3. The battery voltage is nearly dc so the RMS value is very close to the RC filtered signal value. The power ratios in the right column of table #3 are applied to the total kWH calculation to account for waveform type.

With these corrections, a temperature rise per kWH calculation was made for each set of test data. Figure #5 is a scatter plot of the results, representing 46 cases (the data of two cases were lost due to recording error). This plot shows a slightly cooler (more efficient) energy transfer for the pulsed charger. The discharge pattern is contrary to the beginning hypothesis, with the lowest temperature rise going with the dc discharge. The trends, however, are much smaller than the measurement scatter in both charging and discharging cases.

Figure 6 compares the temperature rise per kWH against the average power rate at which the energy transfer took place. The power rate of the pulse charger was higher than the standard charger rate and, while the average discharge currents were equivalent, the RMS currents of the two pulsing discharges were higher than the DC discharge by 21% (50% duty square wave). Included in figure #6 are lines for the efficiency per kW load and the internal losses. Both were calculated assuming a simple voltage source and internal resistance for the battery. Using the data from several tests, the average battery voltage was 237 V and internal resistance was 0.106 Ω . Deviation from the expected loss line would be an indication of pulse circuit improvements on battery efficiency over the normal losses of a static resistor impedance. Only the slightest pattern is discernible and the data is dominated by sampling scatter. As the right axis shows, the range of power input is only a few hundred watts to the mass of the battery at 2,490 kg (5,480 lb).

Considerations for further testing

Two directions are suggested for future research efforts. A similar test could be conducted for high rate charging and discharging. When the battery's energy exchange limits are pushed, pulse and depolarizing techniques may allow wider operating regimes. If so, smaller batteries may be capable of even higher power density, attributable to power conditioning. Such testing will require a proper sizing of the test circuitry including the battery jumper wiring, and the control case for charging would have to be similarly sized for the higher power rate.

A second area of research concerns the waveform effects on lead sulfate management and would address the longer range sulfate issues. The object would be to eliminate the "finishing" charge, currently required to assure sulfate breakdown and re-absorption. Many applications do not lend themselves to a periodic overcharge (finishing) in the course of energy cycling. This leads to battery degradation in such cases as sulfate precipitates accumulate. In general, the heat generation, water gassing, and plate corrosion which are necessarily associated with the finishing charge could be avoided by a conditioning method which operates during partial charge cycling.

Conclusions

An investigation was made into the exploitation of pulsed currents to improve the performance of flooded lead-acid batteries. A round of tests was then conducted to measure the adiabatic temperature rise in transit batteries, using two methods of charge and three methods of discharge at moderate power. These tests failed to show measurable differences which might confirm reduced losses in the battery using pulsed methods. However, the testing did not deal with the questions of high charge/discharge rates, or the longer term issues of sulfate accumulation.

Acknowledgements

The contributions of Ken Cox in tirelessly carrying out the test procedures are gratefully acknowledged.

Testing was done at CARTA by the author and the Electric Transit Vehicle Institute (ETVI) under contract #MDA972-94-2-0003, Southern Coalition for Advance Transportation (SCAT), Atlanta, GA.

Testing reported here was part of an investigation by the author for the masters thesis, *Battery Circuit Performance Using Pulsed Switching*, December 1997, The University of Texas at Austin.

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Table 1. KW Powersource 216 V battery composition [14]

# of cells, flooded lead acid	108 ea
# of container units, steel	4 ea
Total mass	5,480 lb
Steel	1,280 lb, 23.4%
Lead / lead-dioxide	2,990 lb, 54.6%
Electrolyte, acid	1,096 lb, 20.0%
Cell casing, plastic	113 lb, 2.10%

Table 2. Average duration and temperature rise of each charge/discharge method

	Duration (min)	Temperature (°C)
Standard charger	289	13.0
Pulse charger	202	12.0
DC discharge	180	1.4
1 Hz discharge	188	2.4
200 Hz discharge	182	2.6

Table 3. Ratio of RMS of direct recorded signal to RC-averaged signal

	V_{battery}	I_{battery}	VI
120Hz chg	0.999	1.307	1.307
EPTI chg	0.996	1.300	1.295
DC	1.003	1.058	1.061
1 Hz	0.998	1.512	1.509
200 Hz	1.003	1.488	1.492