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PULSE CHARGING OF LEAD-ACID TRACTION CELLS

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May 1980

Prepared for
U.S. DEPARTMENT OF ENERGY
Conservation and Solar Applications
Transportation Energy Conservation Division

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PULSE CHARGING OF LEAD-ACID TRACTION CELLS

by John J. Smithrick

E-454

SUMMARY

Pulse charging, as a method of rapidly and efficiently charging 300 amp-hour lead-acid traction cells for an electric vehicle application was investigated. A wide range of charge pulse current square waveforms were investigated and the results were compared to constant current charging at the time averaged pulse current values. Representative pulse current waveforms were: Positive waveform-peak charge pulse current of 300 amperes (amps), discharge pulse-current of zero amps, and a duty cycle of about 50%; Romanov waveform-peak charge pulse current of 300 amps, peak discharge pulse current of 15 amps, and a duty cycle of 50%; McCulloch waveform - peak charge pulse current of 193 amps, peak discharge pulse current of about 575 amps, and a duty cycle of 94%. In addition, experiments were undertaken to define the effect of peak charge pulse current, peak discharge pulse current, duty cycle and pulse frequency for a Romanov type waveform. For each of the above methods the charge was terminated when either 10% of the charge pulse current produced gas or the cell temperature reached 120°F.

In order to explore ways to improve the energy and ampere-hour (amp-hour) efficiency of pulse charging a limited study of two alternate methods of charging were compared. In method 1 the cell was pulsed throughout the entire charge. In method 2 the cell was initially charged at a constant current, and after the onset of gassing was switched to pulse charging.

Experimental results indicate that on the basis of amp-hour efficiency, pulse charging offered no significant advantage as a method of rapidly charging 300 amp-hour lead-acid traction cells when compared to constant current charging at the time average pulse current value. There were, however, some disadvantages of pulse charging in particular a decrease in charge amp-hour and energy efficiencies and an increase in cell electrolyte temperature. The constant current charge method resulted in the best energy efficiency with no significant sacrifice of charge time or amp-hour output. Whether or not pulse charging offers an advantage over constant current charging with regard to the cell charge/discharge cycle life is unknown at this time.

INTRODUCTION

Recently there has been a growing interest in electric vehicles as a mode of urban transportation. This interest has been precipitated by a shortage of domestic oil, and by a more pollution conscious society. For an electric vehicle to be successful it must, of course, be accepted by potential users. The range on a single charge of typical electric vehicles of today with the present generation of lead-acid batteries is limited. For many potential users and to stimulate a reasonable market penetration it is essential to extend this limited range. One method of increasing the dailey range of an electric vehicle and its utilization may be to rapidly recharge the battery at a suitably equipped on-the-road service station in a similar manner as internal combustion powered vehicles now refuel with gasoline at a

service station. Various methods of rapidly charging batteries have been proposed and reviewed (1,2,3,4,5,6,7,8). One proposed method is pulse charging. Some investigators claim good results while others claim it provides no advantage. Since data reported by both groups is very limited, and inconclusive, an investigation was undertaken and reported herein, to clarify the effect of pulse charging on 300 ampere hour (amp-hour) lead-acid traction cells. Primary interest was in the charge time and energy efficiency.

EXPERIMENTAL

SCOPE OF EXPERIMENT - Three distinct but closely related series of experiments were conducted in this investigation. 300 ampere-hour lead-acid traction cells were used in all cases.

The first pulse charge experiment was conducted primarily to evaluate the effect of substantially different pulse charge waveforms on charge time and energy efficiency. The pulse charge methods were compared to a constant current method at the time average pulse current value. The pulses were limited to different square waveforms, which were classified as positive, Romanov, and McCulloch pulse waveforms. These are illustrated in Figure 1. Although all are square each is unique.

The second pulse charge experiment was conducted to define the effect of peak charge pulse current, peak discharge pulse current, duty cycle and pulse frequency for a Romanov type waveform. Initially peak charge pulse currents of 500 and 300 amperes (amps) were used. However, the 500 amp current resulted in a rapidly rising temperature

which quickly exceeded the 120°F temperature limit. Therefore, a peak charge pulse current of about 300 amps was used as an upper limit for the remainder of the experiments which were as follows: 1) the peak discharge pulse current during the charge was varied from zero to about 37 amps, 2) the duty cycle was varied from 50 to 94%, while maintaining the peak discharge pulse current set at about 14 amps, 3) the frequency was varied from 0 to 400 hz; peak discharge current pulse set at about 14 amps. The frequency was limited to 400 hz because above this value the waveform began to degrade. Pulse charging, which introduces a negative pulse during a constant current charge, can be inherently inefficient because the energy extracted during the negative phase of the charge pulse is sacrificed. The third pulse charge experiment was conducted in order to explore ways of improving the efficiency of pulse charging. The results of a limited study of two alternate methods of pulse charging were compared. In method 1 the cell was Romanov pulse charged from the start until 20% of the charge current produced gas; at which point the charge was terminated. In method 2 the cell was initially constant current charged at the time average Romanov pulse charge current rate of method 1 until 10% of the current produced gas. At this point the charge method was switched to the Romanov waveform of method 1 and continued until 20% of the current produced gas.

CELL CHARGER - The cell charger used is versatile and allows for operation in either the direct current or pulse current mode (9). A wide range of charge current, discharge current, and pulse timing in

either direct current or pulse mode is available.

The charger has the following characteristics:

1. A charge current from 0 to 1000 amps.
2. A discharge current from 0 to 1000 amps.
3. Charge and discharge current pulse frequency from 0 to 1000 hertz.
4. Continuously variable discharge time from 0.1 to 100 milliseconds.
5. Operates in either continuous charge or continuous discharge mode.

The current is controlled with a water cooled high current transistor switch. The transistor switch is capable of carrying 1000 amps dc as well as switching 1000 amps at a 1000 Hz rate. Water cooling is provided for all of the solid state power components in order to obtain the compact, low parasitic inductance configuration necessary for high rate, high current switching.

MEASUREMENTS AND PROCEDURES

During the pulse charge experiments the quantities measured and their accuracies were as follows: cell temperature ($\pm$1°C limit of error); cell gassing rate ($\pm$0.5%); amp-hours ($\pm$0.5%); cell discharge voltage ($\pm$0.5%); cell charge pulse voltage ($\pm$3%); charge pulse current ($\pm$0.5%); discharge pulse current ($\pm$0.5%); and discharge current ($\pm$0.3%).

Cell temperature was measured using iron-constantan thermocouples located in the cell electrolyte. They were coated with epoxy to prevent attack by the sulfuric acid electrolyte.

Cell gassing rates were measured during charge using a calibrated laminar flowmeter (0 to 300 cm^3/min at 21°C, 760 mm of Hg). Since flow rate depends on gas temperature, the cell gas was heated to a constant 65°C via a heat exchanger prior to entering the flowmeter. Flow rates were then corrected to standard conditions, i.e., 21°C and 760 mm of Hg.

Since a charge pulse current generates gas in a pulse mode, the laminar flowmeter averages the flow rate (10). However, the flow rate desired for charge termination is peak flow rate due to peak charge current. Hence a relationship was derived for the peak flow rate in terms of the measured average flow rate. This relationship enables charge termination at the desired gas rate. The gas evolved by the lead-acid cell was assumed to be about 67% H_2 and 33% O_2 by volume (1).

During pulse charging the total amp-hours into the cell during the positive pulses, and the total amp-hours taken out of the cell during the negative pulse were measured separately with an amp-hour meter.

The amp-hour efficiency was calculated as a ratio of the total amp-hour output of a cell during discharge to the total amp-hours put into the cell during charge. The amp-hour output of a cell was obtained by discharging it after a charge was completed, at decreasing current levels to a 1.75 volt cut off. The amp-hour output at each current level was obtained from the amp-hour meter and totalled. A typical discharge amp-hour determination and the current used for

these measurements are shown in Table 1. The total amp-hours delivered to the cell during charge was obtained from the amp-hour meter.

Energy efficiency was calculated as a ratio of the total electrical energy output of the cell during discharge to the total electrical energy into the cell during charge. The energy input during charge was calculated as follows: perodically during the charge the charge pulse voltage was measured across the cell terminals with a calibrated oscilloscope. The oscilloscope traces were photographed at the same time as the amp-hours into the cell, and charge times were recorded. Plots of the peak cell charge voltage, and amp-hours into the cell as a function of charge time were made. The resulting curves were divided into intervals; for each interval the average peak charge voltage and the amp-hours into the cell were obtained. The total energy into the cell was calculated as the summation, over the intervals, of the product of the amp-hours and average peak charge voltage. The total electrical energy output of a cell at discharge was calculated in a similar manner, except the time averaged cell discharge voltage was obtained from a strip chart recording.

Prior to the start of charge, the peak charge and discharge current, pulse frequency, and duty cycle were set at the charger. The peak charge pulse current was verified by calculating the ratio of the positive charge pulse current ampere-hours into the cell, at the end of charge, to the product of the total charge time and duty cycle. The discharge peak pulse current during charge was verified in a

similar manner. The pulse current waveforms were verified by viewing and photographing the waveshapes measured across a non-inductive current shunt using a calibrated oscilloscope. A charge was terminated when either 10% of the charge pulse current produced gas or the cell electrolyte temperature reached 120°F. During charge and discharge the cell temperature was monitored and recorded but not maintained constant.

RESULTS AND DISCUSSION

EXPERIMENT 1

Representative square waveforms used in this charge experiment are illustrated in Figure 1. The waveforms are substantially different, for instance for the Positive waveform the peak charge pulse current was 300 amps, the discharge pulse current was zero and the duty cycle was 50%. For the Romanov waveform the charge peak pulse current was also 300 amps. The discharge pulse current was 15 amps and the duty cycle was also 50%. For the McCulloch waveform the peak charge pulse current was 193 amps, the peak discharge pulse current was 575 amps, and the duty cycle was 94%. For the Constant current waveform the charge current was set at 140 amps, which was the time average pulse current of each of the pulse waveforms. Since the average charge current for all of the above waveforms was the same, a comparison of the effectiveness of the four charge wveform methods was possible. The pulse frequency of each of the waveforms was 60 HZ.

The results of charging 300 amp-hour lead-acid traction cells using

these substantially different waveforms are summarized in Table 2. This data indicate on the basis of charge time, percentage of rated amp-hours capacity charged, and amp-hour output on discharge, that pulse charging offered no significant advantage, as a method of rapidly charging these types of cells, when compared to the constant current charge method. However, as indicated in Table 2, there were some disadvantages such as a decrease in charge amp-hour and energy efficiencies, and an increase in cell electrolyte temperature.

The constant current charge method resulted in the best energy efficiency with no significant sacrifice of charge time, or amp-hour output on discharge when compared to the pulse charge methods. The McCulloch type pulse charge method resulted in the worst energy efficiency which was, on the average about 24% less than the constant current charge method. To summarize from Table 2, for a 300 amp-hour lead-acid traction cell using the different charging waveforms, the range of values obtained were: 1) 61%-63% of rated amp-hour capacity charged, 2) a charge time of 75-78 minutes, 3) an amp-hour output on discharge of 184 to 190 amp-hours, and 4) an energy efficiency of 61% to 80%. Unfortunately the advantages or disadvantages of pulse charging waveforms, compared to constant current charging, on cell charge/discharge cycle life are unknown at this time.

EXPERIMENT 2

This experiment was undertaken for a Romanov waveform to define the effect of peak charge pulse current, peak discharge pulse current,

duty cycle, and pulse frequency on amp-hour and energy efficiency. The results for a representative cell are summarized in Table 3 and are illustrated in Figures 2-4. This data indicate that for a Romanov type wvaeform, with respect to amp-hour output, there was no significant effect of discharge pulse current, or pulse frequency. There was on the average, a 12% improvement in amp-hour output at the 50% duty cycle when compared to the 94% duty cycle. However, with respect to energy efficiency there was on the average, a 21% improvement at the zero discharge pulse current when compared to the aveage 36 amp discharge pulse current and on the average, a 7% improvement in energy efficiency at the 94% duty cycle when compared to the 50% duty cycle. There was, however, no significant effect of pulse frequency. For the 94% duty cycle charge there was, on the average, about a factor of two reduction in charge time when compared to the 50% duty cycle charge. The electrolyte temperature at the end of charge for this case was, on the average, about 6°F higher and the amp-hour output on discharge was on the average about 11% lower. This reduction in charge time was probably due to increased time averaged charge current.

EXPERIMENT 3

A limited experiment was undertaken to explore ways of improving the energy efficiency of pulse charging. The results of two methods called method 1 and method 2 were compared. These methods have already been fully described in the experimental section. Briefly, in method 1 the cell was pulse charged for the entire duration of the

charge. In method 2 the cell was initially constant current charged and switched to Romanov pulse charging at the onset of gassing.

Results of this limited study are summarized in Table 4. This data indicate method 2 was 1.% more energy efficiency than method 1 with no significant sacrifice of charge time, or amp-hours output of the cell on discharge.

CELL TEMPERATURE

The cell temperatures were monitored and recorded during the experiments (Series 1,2,3) but were not controlled. They are summarized for the beginning and end of charge in Tables 1-3. This matches reality since in actual applications of traction cells in electric vehicles, golf carts, or fork lifts, the battery temperature is not controlled during charge or discharge. Also cell temperature is one factor which is influenced by a particular charge method since it is related to efficiency and would be masked by a controlled temperature test. As indicated in Table 2 the lowest cell electrolyte temperature was obtained using the constant current charge method, and was, on the average about 101°F. In contrast, the highest cell electrolyte temperature was obtained using the McCulloch type charge method, and was on the average about 119°F. For all tests, discharges were performed at the same rates, and as expected, the cell temperature variation was minimal.

CONCLUDING REMARKS

Pulse charging offered no significant advantage as a method of rapidly charging 300 amp-hour lead-acid traction cells when compared to constant current charging at the time average charge pulse current value. However, there were some disadvantages such as a decrease in charge amp-hour and energy efficiencies and increase in cell electrolyte temperature. Whether or not pulse charging offers an advantage over constant current charging with respect to cell charge/discharge cycle life is unknown at this time.

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Table 1
Ampere-Hour Output Determination of a Representative
300 Ampere-Hour Lead-Acid Traction Cell

Discharge Current Amps	Amp.-Hrs. Output	Voltage* (Volts)
100	138.9	1.75
75	23.9	1.75
50	24.0	1.75
Total	186.8	

*Voltage at which discharge was terminated.

Table 2
Results of Charging 300 Ampere-Hour
Lead-Acid Traction Cells Using Representative Waveforms

Cell	Charge Wave Form	Pulse Charge Current (Amps)	Pulse Discharge Current (Amps)	Average Pulse Charge Current (Amps)	Duty Cycle (%)	Pulse Frequency (Hz)	AH_1[1]	AH_2[2]	AH_0[3]	Amp-Hr Eff $\frac{AH_0}{AH_1}$ (%)	Energy Eff. (%)	% Charged $\left(\frac{AH_1-AH_2}{300}\right)$	Charge Time (Min)	T_1[4] (°F)	T_2[5] (°F)
102	Constant Curr. (Fig.1)	147	0	147	100	0	190	0	190	100	80	63	78	78	102
102	Positive Pulse (Fig.1)	298	0	147	49	60	190	0	187	98	70	63	78	77	112
102	Romanov Pulse (Fig. 1	305	15	145	50	60	198	10	187	94	67	63	78	75	112
102	McCulloch Pulse (Fig.1)	193	573	147	94	60	227	43	184	81	61	61	75	78	120
103	Constant Curr. (Fig. 1)	146	0	146	100	0	196	0	196	100	79	65	81	74	99
103	Positive Pulse (Fig. 1)	303	0	151	50	60	192	0	194	101	72	64	76	73	112
103	Romanov Pulse (Fig. 1)	309	15	148	50	60	214	10	198	93	65	68	83	74	114
103	McCulloch Pulse (Fig 1)	193	577	147	94	60	236	45	190	81	60	64	78	74	117

1. Total Amp-Hrs into cell during positive pulse
2. Total Amp-Hrs out of cell during negative pulse
3. Total Amp-Hrs out of cell at discharge, after completion of a charge
4. Temperature of cell electrolyte at start of charge
5. Temperature of cell electrolyte at end of charge

Table 3
Effect of Duty Cycle, Pulse Discharge Current,
and Pulse Frequency on Amp-Hour and Energy Efficiency of 300 Amp-Hr Lead-Acid Traction Cells

Cell	Charge Wave Form	Pulse Charge Current (Amps)	Pulse Discharge Current (Amps)	Duty Cycle (%)	Pulse Frequency (Hz)	AH_1[1]	AH_2[2]	AH_0[3]	Amp-Hr Eff. AH_0/AH_1 (%)	Energy Eff. (%)	% Charged $\left(\frac{AH_1-AH_2}{300}\right)$	Charge Time (Min)	T_1[4] (°F)	T_2[5] (°F)
EFFECT OF DUTY CYCLE														
102	Romanov (Fig. 1)	305	15	50	60	198	10	187	94	67	63	78	74	112
102		303	15	75	60	182	3	178	98	-	60	48	78	119
102		303	6	94	60	166	.2	165	99	71	55	35	74	120
103		309	15	50	60	214	10	198	93	65	68	83	74	114
103		305	14	75	60	191	3	188	98	69	63	50	76	118
103		309	11	94	60	179	.4	179	100	70	60	37	74	118
EFFECT OF PULSE DISCHARGE CURRENT														
102	Romanov (Fig. 1)	298	0	49	60	190	0	187	98	70	63	78	77	112
102		305	15	50	60	198	10	187	94	67	63	78	74	112
102		304	35	50	60	215	25	189	88	63	63	85	76	114
103		303	0	50	60	192	0	194	101	72	64	76	73	112
103		309	15	50	60	214	10	198	93	65	68	83	74	114
103		303	37	50	60	227	28	190	84	55	66	90	76	117
EFFECT OF PULSE FREQUENCY														
103	Romanov (Fig. 1)	293	14	50	8	210	10	200	95	67	67	86	73	113
103		309	14	50	60	214	10	198	93	65	68	83	74	114
103		302	10	51	200	205	7	196	96	67	66	80	71	112
103		294	10	52	400	204	7	193	95	67	66	80	72	113

1. Total Amp-Hrs into cell during positive pulse
2. Total Amp-Hrs out of cell during negative pulse
3. Total Amp-Hrs out of cell at discharge, after completion of a charge
4. Temperature of cell electrolyte at start of charge
5. Temperature of cell electrolyte at end of charge.

Table 4
Results of Charging 300 Amp-Hr Lead-Acid
Traction Cell 103 by Method 1[1] and Method 2[2]

Method	Description	Pulse Charge Current (Amps)	Pulse Discharge Current (Amps)	Duty Cycle (%)	Pulse Freq. (Hz)	AH_1[3]	AH_2[4]	AH_0[5]	Amp-Hr Eff. AH_0/A_1 (%)	Energy Eff. (%)	% Charged $\frac{AH_1-AH_2}{300}$	Charge Time (Min)	T_1[6] (°F)	T_2[7] (°C)
1[1]	Ramonov Pulse	303	15	50	60	228	11	211	93	65	72	90	72	111
2[2]	Constant Current	146	0	100	0	192	0	-	-	-	-	79	73	98
	Ramonov Pulse	301	12	50	60	25	1.0	-	-	-	-	10	98	101
					Total	217	1.0	206	95	72	72	89		

1 Method 1. - cell pulse charged from start of charge
2 Method 2. - cell initially constant current charged and switched to pulse charging at the onset of gassing
3 Total Amp-Hrs into cell during positive pulse
4 Total Amp-Hrs out of cell during negative pulse
5 Total Amp-Hrs out of each cell at discharge, after completion of a charge
6 Temperature of cell electrolyte at start of test
7 Temperature of cell electrolyte at end of test

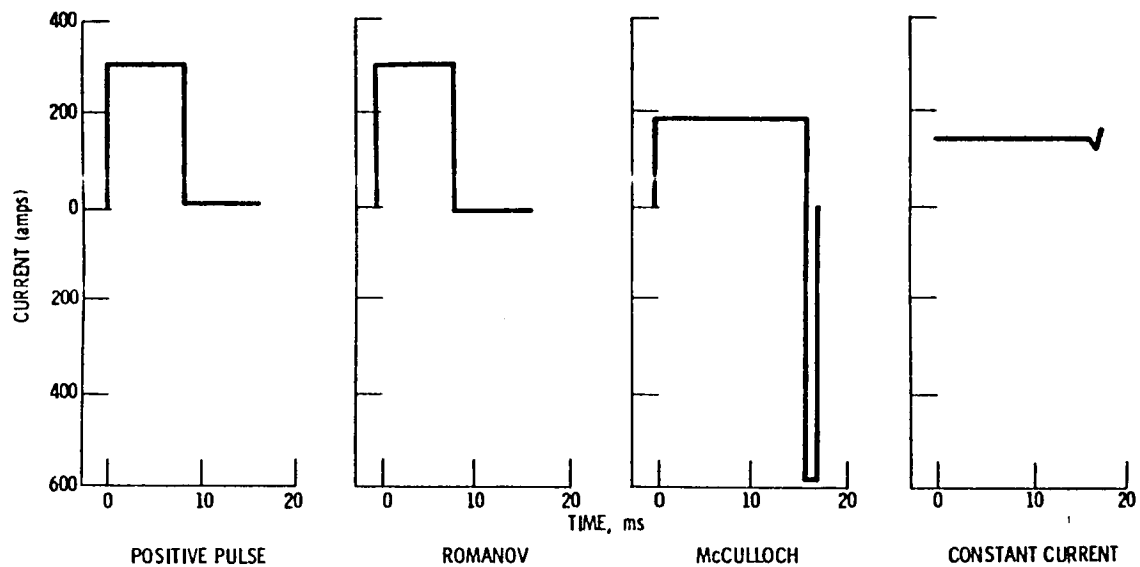

Figure 1. - Representative waveforms used to charge 300 ampere-hour lead-acid traction cells.

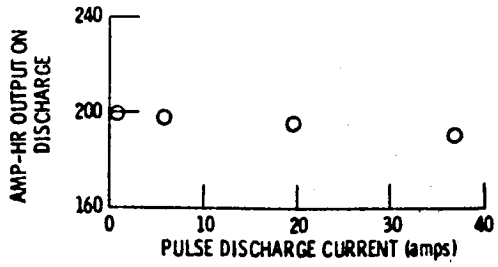

Figure 2. - Ampere-hour output of a representative 300 amp-hr lead-acid traction cell as a function of pulse discharge current during charge.

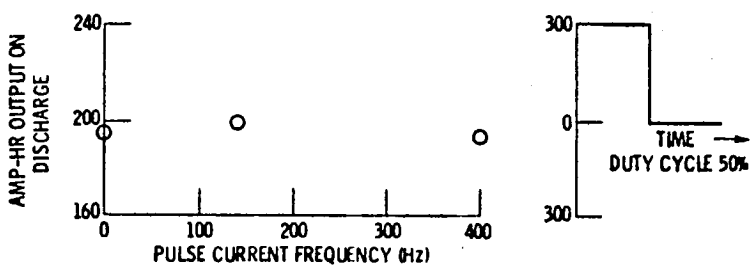

Figure 3. - Ampere-hour output of a representative 300 amp-hr lead-acid traction cell at discharge as a function of pulse current frequency.

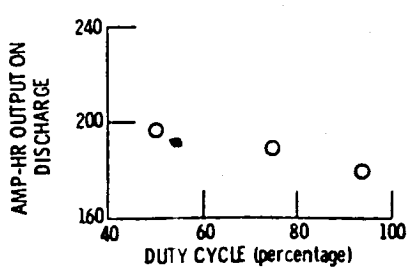

Figure 4. - Ampere-hour output of a representative 300 amp-hr lead-acid traction cell at discharge as a function of duty cycle.

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16. Abstract

Pulse charging, as a method of rapidly and efficiently charging 300 amp-hour lead-acid traction cells for an electric vehicle application was investigated. A wide range of charge pulse current square waveforms were investigated and the results were compared to constant current charging at the time averaged pulse current values. Representative pulse current waveforms were: Positive waveform-peak charge pulse current of 300 amperes (amps), discharge pulse-current of zero amps, and a duty cycle of about 50%; Romanov waveform-peak charge pulse current of 300 amps, peak discharge pulse current of 15 amps, and a duty of 50%; McCulloch waveform - peak charge pulse current of 193 amps, peak discharge pulse current of about 575 amps, and a duty cycle of 94%. In addition, experiments were undertaken to define the effect of peak charge pulse current, peak discharge pulse current, duty cycle and pulse frequency for a Romanov type waveform. For each of the above methods the charge was terminated when either 10% of the charge pulse current produced gas or the cell temperature reached 120° F. In order to explore ways to improve the energy and ampere-hour (amp-hour) efficiency of pulse charging a limited study of two alternate methods of charging were compared. In method 1 the cell was pulsed throughout the entire charge. In method 2 the cell was initially charged at a constant current, and after the onset of gassing was switched to pulse charging. Experimental results indicate that on the basis of amp-hour efficiency, pulse charging offered no significant advantage as a method of rapidly charging 300 amp-hour lead-acid traction cells when compared to constant current charging at the time average pulse current value. There were, however, some disadvantages of pulse charging in particular a decrease in charge amp-hour and energy efficiencies and an increase in cell electrolyte temperature. The constant current charge method resulted in the best energy efficiency with no significant sacrifice of charge time or amp-hour output. Whether or not pulse charging offers an advantage over constant current charging with regard to the cell charge/discharge cycle life is unknown at this time.

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