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Application of pulse charging techniques to submarine lead-acid batteries

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Abstract

The development of pulse charging equipment for the unique application to submarine lead-acid batteries is described. A prototype pulse charger has been developed and applied to individual twin-cell submarine batteries, plus a 20 twin-cell pulse charger has been commissioned at the battery manufacturing facility. The paper provides a description of the pulse charging equipment and preliminary test results and analyses using the prototype twin-cell pulse charger, based on application of a range of positive and negative pulse parameters. The tests so far indicate potential benefits may arise from this form of charging, including enhancement of battery charge levels, reduced gas charging (Stage 3) times and reduced gas evolution rates.

Keywords: Submarine; Lead-acid batteries; Pulse charging

1. Introduction

The main storage battery (MSB) on the Collins Class submarine consists of flooded lead-acid battery cells. The submarine has a large number of cells connected in series and is divided into four battery sections each rated at a nominal 440 VDC. Charging routines for the Collins Class submarine batteries are based on a PEI regime (constant power, constant voltage, constant current/gas charging). The submarine is designed to use only the first two stages at sea with Stage 3, constant current/gas charging used prior and post deployment. At sea cycles of constant power charging (10–12) followed by a Stage 2 constant voltage maintains a high SOC and high charging efficiency. Stage 3 constant current/gas charging only returns about 3% of the battery capacity and has very low charging efficiency (15%).

Inherent small variations in cell impedance result in cells having slight differences in capacity and self-discharge rates. These variances can lead to imbalances in cell SOC, which will become accentuated over extended deployments. Periodic Stage 3 gas charging is necessary to equalise the cells, and to remove sulphate build up to restore cell capacity and performance. During extended deployments it may become necessary to conduct remedial charging at sea to restore cells impacted by the imbalance.

Investigative testing on end of life cells has shown, as would be expected, that positive plate corrosion was advanced, possibly the result of overcharging at high voltage (gas charging) and high operating temperatures. To address this issue the RAN initiated the development of pulse charging techniques for submarine batteries due to the potential to reduce the gas charging time to reach full SOC.

2. Review of pulse charging literature

Lam et al. [1] offered the following explanation of their findings. During normal charging using constant current, crystals will form at active sites because they require less deposition energy. As the current continues, the crystal will become progressively larger. The larger crystals formed during constant current charging lead to a lower surface area of the active mass. Yamashita and Matsumara [2] have demonstrated that the reactivity of the active mass is decreased when

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such crystals are formed. Both of these factors work to lower the capacity of the battery.

Yamashita and Matsumara [2] also refer to Pavlov's gel zone theory. Pavlov [3] proposed that the active material consists of PbO_2 crystals connected by $PbO(OH)_2$ gel zones. These gel zones form a current carrying bridge between agglomerates. As the active mass becomes increasingly crystalline the conductivity decreases.

With high pulsed current charging, average voltage is similar, but instantaneous voltage is much higher. This increased driving force allows crystals to form more randomly and rapidly. During current off-time, the crystal growth will cease. Upon current being applied again, new crystals will form as opposed to existing ones continuing to grow. Therefore, crystals are prevented from becoming large and capacity is maintained.

Briggs [4] claims that most forms of reduction of capacity and charging efficiency are brought about by ionic unbalance in lead-acid batteries. This is caused by the disproportionate loss of hydrogen and oxygen gas molecules, which leads to crystallisation of the active material and other negative effects. The use of pulsed charging helps to offset this ionic unbalance and leads to improved cell performance.

Podrazhansky and Popp [5] claim that multiple discharge pulses should be used "... so that natural chemical and electrical gradients within the battery will serve to disperse the ions more evenly throughout the electrolyte". They also claim that short duration charging pulses create small size crystals (therefore greater surface area) with no sharp edges. Discharge pulses tend to remove sharp edges on a crystal so it is possible to obtain the smaller size crystals with rounded edges using longer duration charging pulses and short, high magnitude discharge pulses.

Preliminary tests on the Collins Class submarine batteries have indicated that only frequencies in the range 0.1–100 Hz would be beneficial. It also needs to be noted that we have found no record of pulsed charging of large lead-acid batteries of a size comparable with submarine batteries. This does not necessarily show that such tests have not been performed. Some research organizations may have tried pulsed charging of submarine batteries but for a variety of reasons, not published their results.

3. Experimental

A project was initiated to investigate pulsed charging for use on submarine cells [6]. A pulsed charger capable of pulse charging a Collins class twin-cell was developed by Boeing Aerospace Support for the ADF. Note that a twin-cell is two single 2 V cells connected in series and housed in a common container. Initially a prototype pulsed charger was developed, which employed metal oxide semiconductor field effect transistors (MOSFETs) and could produce both positive and negative pulses of amplitude 40 A. This unit was tested using one of the cells of a 6 V car battery, and operated satisfactorily.

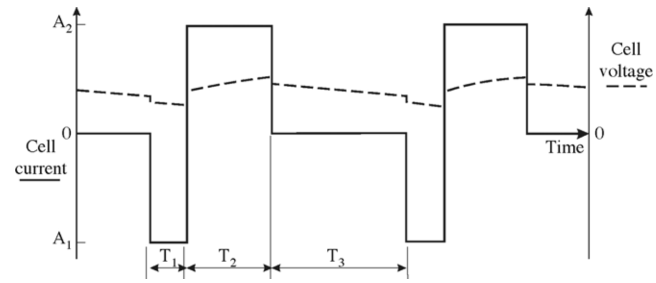

Fig. 1. Ideal pulsed charging waveforms of twin-cell charger.

3.1. Twin-cell pulse charger development

Using the knowledge gained from the prototype unit, a twin-cell pulsed charger was developed based on MOSFET technology. It is capable of applying positive and negative pulses of adjustable amplitudes and durations. The ideal waveform is shown in Fig. 1, where T1 is adjustable from 0 to 200 ms, T2 is adjustable from 0 to 1 s, and T3 is adjustable from 1 to 9999 ms, A1 is adjustable from 0 to −800 A, and A2 is adjustable from 0 to 800 A. The timed-average output charge current is limited to 500 A.

The unit has been satisfactorily demonstrated on twin-cells for the Collins class submarine. A typical charging current waveform with a submarine twin-cell is shown in Fig. 2. Initial tests show a significant reduction in the time taken for Stage 3 charging.

The twin-cell pulsed charger is being used to investigate the effect of pulsed charging, with the following priorities:

(a) Testing similar cells to the same cycle regime, one with pulsed charging and one with conventional charging.
(b) Use of pulsed charging to accurately and quickly determine cell state-of-charge.
(c) Variation of pulsed parameters with variation in state-of-charge of battery.
(d) Study effect of negative pulses.
(e) Optimise pulsed parameters to reduce gassing.

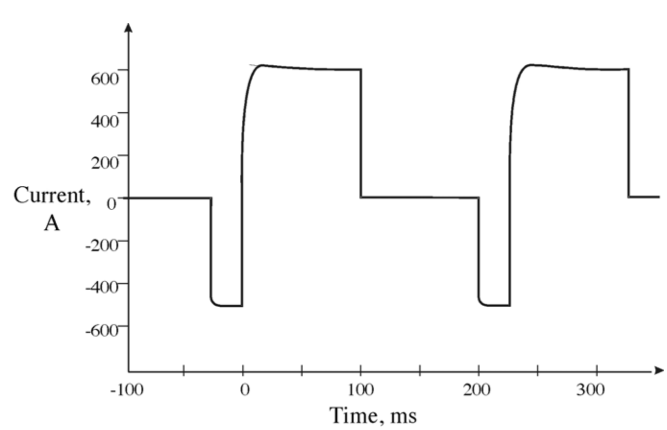

Fig. 2. Typical test current waveform of twin-cell charger.

(f) Determine whether pulsed charging can be used at the beginning of cell life to improve capacity, i.e. at factory acceptance tests (FAT) and after installation.
(g) Determine the effect of pulse charging on the preventive and corrective maintenance of submarine cells.

4. Anticipated benefits of pulsed charging of submarine batteries

The anticipated benefits of the pulsed charging method over the conventional charging method are:

(a) Improved efficiency of Stages 2 and 3 of recharge performed alongside. Reduced time to return battery to top-of-charge, potentially a reduction of 5–10 h for a full normal charge.
(b) Removal of need to perform equalising charges (E-charge). The E-charge is a full normal charge followed by three 2 h equalising gas charges. Removal of the need for the equalising charges implies a saving of 15 h charging every 2–3 months for each battery.
(c) Reduction of gas evolution and water loss.
(d) Improved battery cleanliness, i.e. reduced presence of airborne atomized sulphuric acid in battery compartment during and after a gassing charge.
(e) Reduction in rate of plate corrosion that normally occurs during a gassing charge, which will lead to extended battery life.
(f) Improved conditioning and equalisation of battery cells. This will lead to improved capacity availability, increased rate of charge acceptance (yielding shorter charges at sea) and extended battery life.
(g) More efficient battery manufacturer's commissioning procedure.
(h) Recovery of cells affected by previously irreversible plate sulphation.

The cost savings in benefits (a–e) can be measured in terms of reduced man-hours and materials for battery maintenance as well as increased operational flexibility. But the biggest savings will be derived from benefits (f–i). Extending the life of a battery by even 6 months will have very significant cost benefits to the ADF. This may negate the need for a special docking to replace an entire battery or sections of it, to keep the submarine operational until the programmed docking for refit.

4.1. Submarine battery performance improvement

The twin-cell pulse charger is located at Pacific Marine Batteries. The twin-cell test facility was used to pulse charge two twin-cells that had previously failed the FAT. Tables 1 and 2 below contain each twin-cell's performance characteristics before and after the application of pulse charging.

Two twin-cells (1 and 2 years old) were selected for the initial pulse charge testing using the twin-cell pulse charger. The measured effects of pulse charging resulted in about a 2% increase in capacity compared with the original commissioning FAT capacity tests. The Stage 3 charging time is also significantly reduced when pulse charging was applied.

4.2. Gas evolution rate—twin-cell pulse charger

One of the benefits of pulse charging over conventional continuous current charging is perceived to be a reduction in gas evolution and hence water loss from a lead-acid battery. A series of tests has been carried out on submarine twin-cell to confirm this benefit and to develop optimal pulse settings to achieve the least rate of gas evolution. The rate of discharge and charge of the twin-cell pulse charger was initially limited to 450–500 A (average), so high rates of discharge and recharge were not possible. Recently, additional equipment has been commissioned that enables higher and more realistic rates of discharge and recharge. The twin-cell load bank

Table 1
Battery capacity conventional charging vs. pulse charging (amplitude 700 A reducing to 200 A, duty cycle 25%, 25 Hz)

Cell no.	Commissioning date (FAT)	Capacity at FAT (%)	Test date	Capacity % pulse charging (test 1)	Capacity % pulse charging (test 2)
6-193	January 1999	101.8	March 2001	100.7	100
6-194	January 1999	96.5	March 2001	100.7	100
00-17	July 2000	94.5	April 2001	87.8	99.4
00-18	July 2000	96.8	April 2001	95	98.6

Table 2
Charging time (hours), Stage 3 constant current/pulse charging

Cell no.	Conventional charging time stage 3-gassing (h)	Pulse charging time (test 1) stage 3-gassing (h)	Pulse charging time (test 2) stage 3-gassing (h)
6-193	10–14	2.183	1.133
6-194	10–14	2.183	1.133
00-17	10–14	3.5	3.083
00-18	10–14	3.5	2.333

can discharge a twin-cell up to a maximum of 1000 A. The twin-cell high rate charger can charge a twin-cell up to a maximum of 2500 A. Note that with the twin-cell pulse charger, there is no off-time (or rest period) that can be set between the negative pulse and the positive pulse. The negative pulse (if set) always occurs in the lead up to a positive pulse.

4.3. Test equipment—twin-cell pulse charger

The following test equipment was used for the tests:

- Submarine twin-cell,
- twin-cell pulse charger,
- 2500 A twin-cell charger,
- 1000 A twin-cell load bank,
- fluke 190 scopemeter,
- battery monitoring probe,
- fluke 87 multimeter,
- spirit thermometers,
- glass hydrometers,
- gas flow meter (Ritter TG1 gas meter connected to electronic display unit EDU 32),
- oxygen analyser (Sybron/Taylor servomex O_2 analyser 580 A),
- laptop computer for automatic logging of results.

4.4. Test setup—twin-cell pulse charger

A submarine twin-cell is simultaneously connected to the twin-cell pulse charger, high rate conventional charger and the twin-cell load bank. During discharges, and Stage 1 of the recharges, agitation air is connected to the twin-cell so that electrolyte stratification is prevented. For the second stage of charges, the gas measurement equipment is connected to the most negative of the two cells in the twin-cell. When this is connected, it is neither possible to agitate, nor measure specific gravity in the cell containing the gas measurement equipment. During discharges the gas measurement system is disconnected from this cell so that the other readings can be taken.

After the initial conditioning discharge and recharge, each charge and discharge cycle is carried out in the same way.

4.5. Results—twin-cell gas evolution

Table 3 below indicates the effect of pulse charge frequency on gas evolution compared to a constant current charge at 400 A. The duty cycle was kept constant at 50% (800 A pulse amplitude). The termination voltage for each test was 2.6 V, however, the rate of change of voltage at the end of test is quite rapid which caused the termination of tests to be inaccurate. However, it appears that the gas evolution reduces as the pulse frequency is increased.

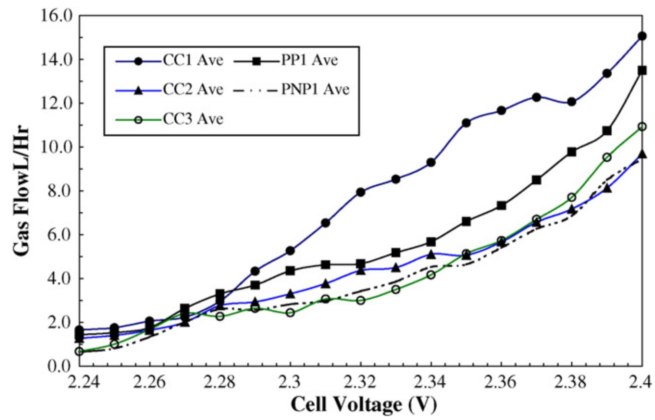

Fig. 3. Gas evolution for constant current and pulse charging.

It must be noted that the twin-cell discharges prior to each charge cycle was 4% capacity of the submarine battery. The constant current charge was actually conducted between the 10 and 100 Hz pulse charging.

The rates of gas evolution versus cell voltage for the various charging routines are shown in Fig. 3. As several charge cycles are performed for each charging routine the gas evolution rates have been averaged to produce a single line plot for each method of charging.

CC1, CC2 and CC3 denote constant current charges. PP denotes pulse charges with positive pulses only. PNP denotes pulse charges with both positive and negative pulses. The charges were conducted in the order shown in the legend. That is, CC1 Ave charges were carried out first (between 7 and 11 May, 2004) and the CC3 Ave charges were carried out last (between 26 and 27 May, 2004).

The first observation that one makes is that the CC1 Ave charges produced significantly higher rates of gassing in the voltage range 2.3–2.4 than any of the other charges. The maximum difference between CC1 Ave and PP Ave is 5 l/h (or 42%) at 2.36 V. The average reduction between 2.3 and 2.4 V is 29.4%. In comparison with the other charges, including constant current charges, the difference is even greater.

The second feature to note in Fig. 3 is that the rate of gas evolution decreases chronologically. The first charges per-

Table 3
Gas evolution variation for varying pulse charging frequency (cell no. A020827)

Charge parameters	Charge time (min)	V_{final} (V)	Hydrogen production (l)	Oxygen production (l)	Normalised hydrogen production (%)	Normalised oxygen production (%)
Constant current (400 A)	125	2.606	6.83	7.27	100	100
PC 0.5 Hz 50% duty cycle	95	2.648	6.97	7.08	102.0	97.4
PC 10 Hz 50% duty cycle	80	2.560	5.75	5.75	84.2	79.1
PC 100 Hz	90	2.613	5.85	5.11	85.7	70.3

formed (CC1 Ave) produced the highest rates of gassing. The second set of charges (PP Ave) produced the next highest rates of gassing. The remaining three sets of charges all produced similar plots and, given the uncertainties of the test set-up, no significant differences can be found between these three.

CC1 Ave charges were conducted on the twin-cell before it had received any form of pulse charging. Subsequently a series of pulse charges with positive pulses only were performed. Constant current charges CC2 Ave and CC3 Ave were identical to CC1 Ave charges and produced significantly lower rates of gassing between 2.3 and 2.4 V. This result appears to confirm the previous assertion that the gas reduction effects of pulse charging are retained by the twin-cell for a number of cycles after the pulse charging have occurred. So, regardless of how the twin-cell is charged (i.e. constant-current or pulsed-current), once it has received some pulse charging the twin-cell displays lower rates of gassing during the charge, particularly between 2.3 and 2.4 V. The number of cycles after the pulse charging that this effect carries on for is still to be determined.

A possible explanation for the decrease in rates of gas evolution observed in Fig. 3 is that the reduction in gas evolution may be a normal feature of a twin-cell which is cycled a number of times after being at rest for a considerable period. For example the production of gas during the 10th or 11th charge may be less than that during the 1st and 2nd charge even if all charges are conducted with constant current. The cycling of the twin-cell has the effect of breaking down some of the large and stubborn crystals of lead sulphate and lead oxide that have formed on the electrodes during storage. The breaking down of these crystals into smaller, useful structures may occur gradually, it is possible that pulse charging speeds up this effect so that less cycles are needed.

It should also be noted that this result is not entirely consistent with previous tests performed. In the latest series of tests we have seen a reduction of gassing when only positive pulse charging was employed. It is possible that the age and cycling history of each twin-cell tested may explain these different observations. In both cases however there has been a reduction in the rate of gas evolution from pulse charging that includes a negative pulse.

4.6. Twenty twin-cell pulse charger development

A 40-cell (20 twin-cell) pulsed charger has been developed and recently commissioned by Alstom Australia. The charger is capable of charging and discharging from four to 40-single submarine cells connected in series. It provides a variable charging voltage from 2.0 to 2.8 V per single-cell, and a variable charging and discharging current from 0 to 1600 A. It is capable of continuously supplying 6.25 kW per single-cell, with a total output power of 250 kW.

The charger is based on insulated gate bipolar transistor (IGBT) technology. The charger has five modes of operation. Mode one provides constant power charging, adjustable from 0 to 6.25 kW per single-cell (i.e. Stage 1 charging). Mode two employs constant voltage charging, adjustable from 2.2 to 2.6 V per single-cell (i.e. Stage 2 charging). Mode three generates constant current charging, adjustable from 50 to 400 A (i.e. Stage 3 charging). Mode four utilises pulsed charging, and the charging and discharging waveforms are independently settable. Mode five provides constant current and constant power discharging.

The 40-cell pulsed charger consists of the following main elements:

(a) DC power source,
(b) power electronics module (PEM),
(c) human machine interface (HMI) and controllers.

Pulsed charge algorithms have been developed by other researchers, e.g. Lam et al. [7] and the patent of Lam et al. [8], which describes a method for fast charging lead-acid batteries using resistance free voltage as the main control parameter.

The fully automated operation and computer control of the 20 twin-cell pulse charger enables the programming (LabVIEW) of various pulse charge algorithms to be evaluated on a large number of twin-cells with the aim of developing an optimum algorithm for pulsed charging submarine cells.

5. Conclusion

Testing on submarine cells indicates that the capacity can be improved with pulse charging. This capacity improvement was obtained immediately for new or relatively new cells. But for older cells (4–5 years old) 15 or more pulse charge cycles were required before capacity improvements were obtained. It appears that the older the cells the more stubborn the sulphation is to break down. And some sulphation is impossible to reverse. Use of pulse charging also indicated that the Stage 3 (gas charging) could be substantially reduced.

Single cell gas evolution tests indicate that the gas evolution reduces with increased pulse frequency. This is more pronounced with the oxygen evolution, which is an important factor for submarine batteries which suffer from positive plate corrosion since oxygen is evolved from the positive plate during gas charging. These tests were conducted after only a 4% (600 A) battery capacity discharge and it is considered that further testing is required with deeper discharges to confirm this result.

Integrating the gas evolution rate to determine the gas evolved in litres can be quite informative and can be used for correlating the evolution of gassing with different charging regimes.

It appears that after the application of pulse charging to a cell the beneficial effects remain even though conventional charge routines are resumed. In order to evaluate the performance of pulse charging it is therefore necessary to baseline the cells performance using conventional charging routines before applying the pulse charging test program.

6. Future testing

Further gas evolution tests are proposed to:

1. Eliminate normal conventional charge cycles as a possible cause of gas reduction.
2. Test the repeatability of the results.
3. Assess the effect of pulse charging duty cycle and pulse frequency (including negative pulse).
4. Determine the effect pulse charging has on charging efficiency. If pulse charging causes a reduction of gas production for the same energy input into the battery cell, then it follows that the charging efficiency is increased. This would be evidenced by reduced charging times and energy input to achieve the same state of charge, in comparison with conventional charging. A series of tests should be performed to determine whether a reduction of gas evolution corresponds to a proportional improvement in charging efficiency.

The following work program will also be implemented in parallel with the continued twin-cell pulse charger testing program:

- Commencement of multiple twin-cell testing using the 20 twin-cell pulse charger.
- Submarine battery network inductance measurement—it is planned to simulate the inductance effect of 99 twin-cells (one battery compartment) and to determine the pulsed degradation and to evaluate this pulsed charging performance. This risk mitigation strategy will ensure that if applied to the submarine that the expected improved performance can be achieved.
- Investigate by autopsy the effect pulse charging has on the crystalline structure of the positive and negative plates of a submarine twin-cell.

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