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Advanced management strategies for remote-area power-supply systems

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Abstract

An operating strategy based on partial-state-of-charge (PSoC) operation has been developed for a remote-area power-supply (RAPS) system in Peru. The facility will power an entire village and comprises a photovoltaic array, a bank of gel valve-regulated lead-acid (VRLA) batteries, a diesel generator, and a sophisticated control system. The PSoC schedule involves operation below a full state-of-charge (SoC) for 28 days, followed by an equalization charge. The schedule has been evaluated by operating a 24 V battery bank under simulated RAPS conditions in the laboratory. It is found that operation between 58 and 83% SoC causes the negative-plate potentials to move to significantly more negative values during charging as the PSoC duty progresses. This behaviour is undesirable, because it can lead to the activation of a preset limit and a subsequent reduction in system efficiency. Lowering the PSoC window to 47–72% SoC or 40–65% SoC during the 28-day cycle is found to stabilize the negative-plate potentials. The behaviour of the negative plates in gel batteries is very similar to that observed for absorptive glass mat (AGM) designs of VRLA batteries operated in hybrid electric vehicles.

Keywords: Gel valve-regulated lead-acid battery; Negative plates; Partial-state-of-charge (PSoC); Peru; Remote-area power-supply (RAPS); Sulfation

1. Powering the Amazon region of Peru

Many people living in the remote regions of developing countries do not have access to reliable power. In most instances, the normal method of supplying power, i.e., via a mains grid, is not practical due to a variety of reasons. One alternative to this approach is to install remote-area power-supply (RAPS) systems. In areas where people live close together in a village, one large system can power the entire village via a mini-grid. Such systems typically comprise a large battery bank, a diesel generator, a photovoltaic (PV) array and/or wind generators. Where homes are further apart, individual systems with a 12 V battery, a single PV panel and a simple controller are often employed.

At present, the majority of Peruvians in isolated rural communities use diesel generators to meet their electrification needs. Typically, these units supply energy for only four-to-five hours per day. Also, the generators are expensive to maintain and produce significant quantities of carbon dioxide and other pollutants. In order to provide low-polluting, cost-effective power to people in the Amazon region, a consortium has been formed to develop solar–diesel-generator battery RAPS systems for village electrification. The initiative is known as the Renewable Energy Systems in the Peruvian Amazon Region Programme (RESPAR Programme). A non-profit association, ILZRO RAPS Peru, has been established to oversee work and thereby demonstrate the viability of such large-scale systems.

In the first phase of the RESPAR Programme, a RAPS system has been installed in Padre Cocha in the Loreto Region of Peru. This community was selected because of its awareness of the beneficial impact of the technology and its full commitment to support the RESPAR initiative. As one of the aims of the RESPAR Programme is to reduce the dependence on energy generated by fossil fuels, and thereby decrease associated emissions of carbon dioxide, a large PV array has been included in the RAPS system. The system also comprises advanced long-life batteries, a high-quality electronic control system, and a back-up diesel generator. This approach has been employed to ensure that the system is reliable and that it achieves the required longevity. CSIRO has developed an advanced operating strategy for the Padre Cocha system that should minimize pollution from diesel-generator operation and maximize battery life. The derivation and evaluation of the strategy are described in this paper.

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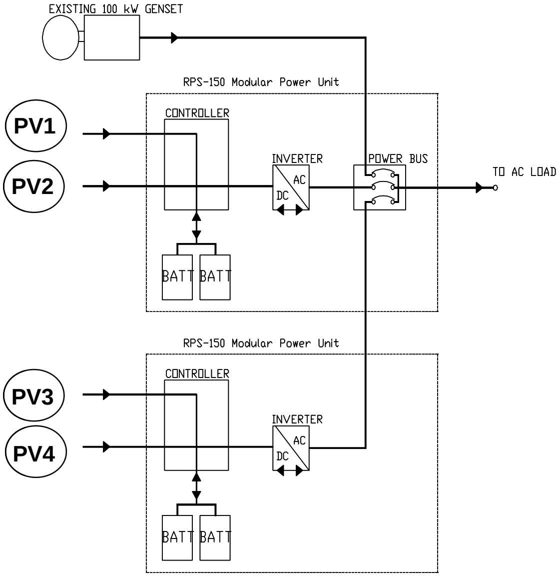

Fig. 1. Configuration of RAPS system at Padre Cocha.

2. System design at Padre Cocha

The proposed RAPS system at Padre Cocha will provide a 24-h basic electricity service (i.e., 300 kWh per day). The design of the system is based on two 150 kWh modules (Fig. 1). Each module comprises the following; (i) a 15 kW PV array; (ii) a 50 kW inverter; (iii) two, 240 V strings of lead-acid batteries with a total nominal capacity of 780 Ah at the 10 h rate. One 100 kw diesel generator supplies power to both modules.

Valve-regulated lead-acid (VRLA) batteries of the gel variety have been chosen for the project, and have been especially designed by Battery Energy Power Solutions (BEPS) and CSIRO for RAPS duty in regions with hot climates. The batteries, called ‘SunGel’, have a nominal capacity of 390 Ah (10-h rate), have thick positive plates (5.5 mm), and are capable of over 1100 cycles (100% depth-of-discharge). The operating efficiency is superior to that of comparable technologies, due to the use of an ultra-pure form of lead, VRLA Refined$^{\text{TM}}$ lead, developed by Pasminco and CSIRO [1]. Further, the batteries can be produced at a competitive cost due to several proprietary manufacturing processes.

3. Algorithm development at CSIRO

It is well known that the success of RAPS systems which utilize renewable energy depends heavily on the reliability and life of the battery energy-storage component. Also, it is accepted that battery management is a critical factor in ensuring good battery life, and that there can be quite a difference between the anticipated and actual duty of the battery in RAPS systems. Hence, in large-scale RAPS facilities, it is of the utmost importance to provide expert technical and scientific information whereby the battery-management system can be designed to produce maximum benefit, not only in terms of optimum battery performance but also in terms of greatest overall system efficiency.

CSIRO has developed a best-practice battery control strategy for the large-scale system at Padre Cocha. The process has involved three stages. First, a simulated load profile was defined. Second, a simulated RAPS operating schedule was formulated by combining the load profile with a partial-state-of-charge (PSoC) operating strategy. This schedule controls the number of cycles performed between full recharges (termed ‘PSoC cycles’), the state-of-charge (SoC) window, and the intensity of the full recharge. Finally, the performance of the simulated RAPS operating schedule was evaluated by conducting cycling tests on a 24-V pack of cells identical to those used at Padre Cocha.

3.1. Development of a simulated load profile

Simulation of the load profile required detailed information on both the expected energy production (e.g., from solar panels and diesel generators) and the energy consumption. Orion Energy Systems (the company responsible for system design and construction at Padre Cocha) and CSIRO have obtained such data through extensive computer modelling and monitoring of existing RAPS facilities in Peru. The resulting daily load profile is shown in Fig. 2. The schedule is intended to represent the flow of power in the RAPS system at Padre Cocha. The values of current shown in the profile are the sum of the discharge and the charge components and are for an individual battery string (note, the battery bank at Padre Cocha uses multiple strings).

The first section of the simulated daily profile is a discharge that arises mainly from the operation of refrigerators and background lighting (00:00–06:30 h, 37.4 Ah removed). The load on the battery increases at 06:30 h, as a result of villagers preparing breakfast, and then decreases gradually until 09:00 h (06:30–09:00 h, 18.8 Ah removed). Between 09:00 and 15:00 h, the power from the solar panels exceeds that required by the villagers and battery charging occurs (09:00–15:00 h, 19.6 Ah returned). At 15.00 h, the battery again undergoes discharge. This continues until 21.15 h, at

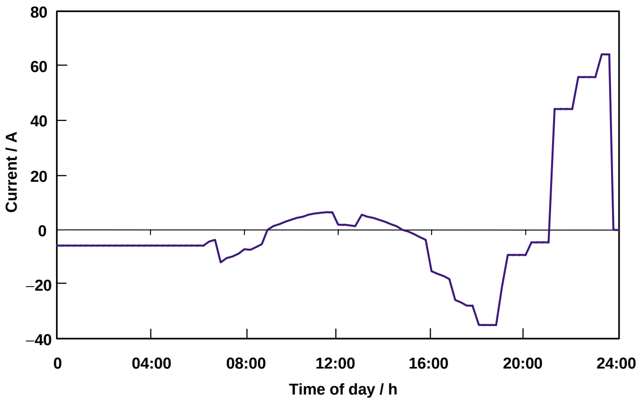

Fig. 2. Simulated daily load profile at Padre Cocha.

which stage the nominal SoC of the battery has decreased to the lowest daily level (15:00–21:15 h, 99.1 Ah removed). The diesel generator is then started and supplies the load whilst also charging the batteries. Charging is continued until the Ah returned is equal to the net Ah discharged during the day.

3.2. *Simulated RAPS operating schedule*

A simulated RAPS operating schedule has been developed by combining the simulated load profile (Section 3.1) with a PSoC operating strategy. The latter controls the number of PSoC cycles between each full recharge, the SoC operating window (known as the 'PSoC window'), and the intensity of the full recharge (called 'equalization'). The number of PSoC cycles between each equalization charge should be as large as practical in order to minimize the run-time of the diesel generator under low-load conditions (i.e., during equalization and constant-voltage charging). The charging time should, however, be sufficient to avoid sulfation of the battery plates. Also, the upper limit of the PSoC window should be set to maximize charge efficiency, and the lower limit should ensure that there is always adequate power to meet the demand without over-discharging the battery. Finally, the equalization charge should be sufficient to recover full capacity, whilst minimizing overcharge and associated electrolyte dry-out (note, from here on, the specified number of PSoC cycles followed by a full recharge is referred to as a 'master cycle').

Drawing on previous experience with RAPS systems, it was decided to adopt the following preliminary strategy: (i) application of 28 PSoC cycles between each full recharge; (ii) evaluation of three different PSoC windows; (iii) application of an equalization charge with a voltage limit of 2.45 V per cell until 100% overcharge is achieved (i.e., until the total number of Ah returned, Ah_{ch}, is equal to that discharged during a master cycle, Ah_{dis}), followed by charging at a constant current of 10 A until a further 1% overcharge is delivered; additional overcharge is added if required.

In detail, the overall operating strategy is as follows:

(i) Discharge at 39 A (10-h rate) until the specified number of Ah are removed, i.e., either 93.4 Ah (PSoC window of 58–83% SoC), 154 Ah (PSoC window of 47–72% SoC) or 192.5 Ah (PSoC window of 40–65% SoC). Note, the PSoC window has been based on the measured 100-h capacity of the battery (i.e., 550 Ah), because the 100-h discharge rate (5.5 A) is close to the average discharge rate during the daily load profile (see Fig. 2).
(ii) Subject the battery to one pass through the daily load profile, i.e., a net discharge–charge of 135.7 Ah (see Section 3.1).
(iii) Repeat (ii) for a total of 28 times.
(iv) Charge the battery at 70 A to a voltage limit of 2.45 V per cell until $Ah_{ch} = Ah_{dis}$.
(v) Charge the battery at 10 A until $Ah_{ch}:Ah_{dis}$ = specified % overcharge.
(vi) Repeat steps (i)–(v).

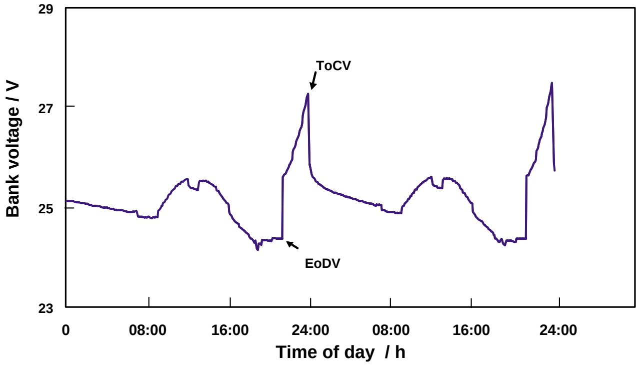

Fig. 3. Voltage of battery bank during day one and two of a typical master cycle.

4. Battery performance under simulated RAPS operating schedule

In order to evaluate and fine-tune the RAPS operating strategy described in Section 3.2, a 24 V battery bank of SunGel cells (nominal 390 Ah at 10-h rate) has been operated under the schedule in the laboratory. Optimization of the equalization and PSoC window components is described in Sections 4.1 and 4.2.

4.1. *Equalization*

The battery was first subjected to 10 conditioning cycles. Each cycle consisted of a discharge at 39 A to 1.8 V per cell, followed by a charge at 40 A with a voltage limit of 2.5 V per cell. Charging was continued until 108% of the previous discharge capacity was returned. The capacity of the bank became stable after the first six cycles; the final four values were between 425 and 430 Ah. Following conditioning, the battery pack was operated according to the schedule described in Section 3.2, with a PSoC window of 58–83% SoC and an equalization of 101% overcharge. The voltage response for the battery bank during this time is shown in Figs. 3 and 4.

The highest voltage reached during the main charge of the daily cycle, called the top-of-charge voltage (ToCV), increased gradually from 27 to 31.5 V throughout the master cycle. This behaviour is undesirable because, in the field, it leads to the activation of a voltage limit and a related decrease in charge current. The net effect is that the output of the diesel generator is restricted (i.e., its load factor decreases), which leads to a decrease in system efficiency and an increase in fuel consumption. Note, although a voltage limit of 2.45 V per cell would normally be imposed in the field to avoid excessive overcharge, no limit was used in these experiments in order to obtain more accurate

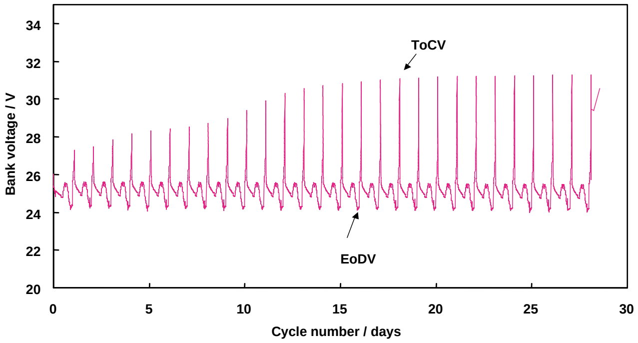

Fig. 4. Voltage of battery bank during typical master cycle.

information on how the ToCV varied with extended PSoC duty. Similar increases in ToCV are often observed when charging flooded batteries that have been operated under PSoC duty. In this instance, however, the behaviour appears after just a few cycles as a result of electrolyte stratification [2]. Given then that gel batteries do not suffer from this phenomenon, it is clear that the increase in ToCV observed during extended PSoC operation (Fig. 4) is caused by some other mechanism.

Increase in ToCV have also been observed for VLRA batteries of the absorptive glass mat (AGM) design that have been operated under hybrid electric vehicle (HEV)

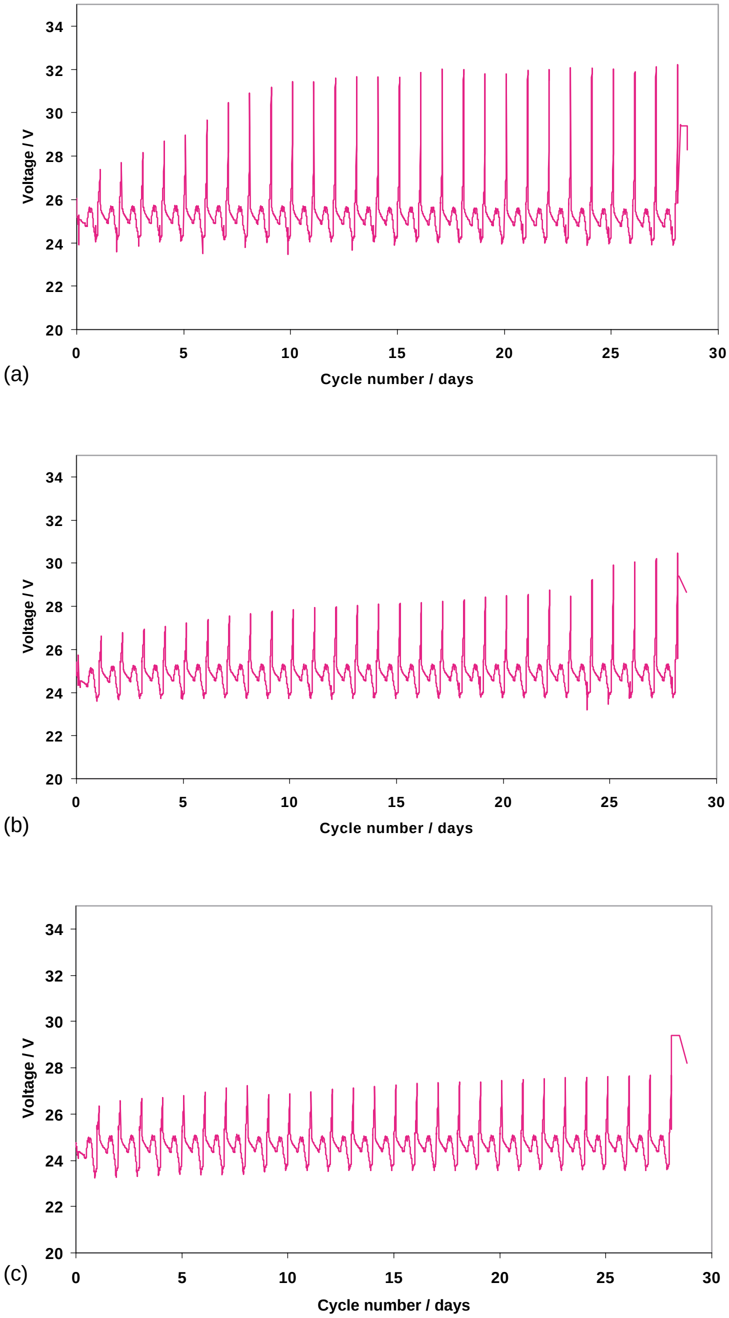

Fig. 5. Voltage during simulated RAPS duty at three different PSoC windows: (a) 58–83% SoC; (b) 47–72% SoC; (c) 40–65% SoC.

Table 1
Summary of master cycles performed by 24-V battery bank

Master cycle no.	Overcharge delivered at end-of-master cycle (%)[a]	Nominal PsoC window (% SoC range)[b]
1	101	58–83
2	101.5	58–83
3	102	58–83
4	102	58–83
5	102	58–83
6	102	47–72
7	102	40–65

[a] All master cycles comprise 28 PSoC cycles.

[b] To calculate the PSoC window, it is necessary to estimate the battery capacity at the average discharge current (10.5 A) of the simulated load profile. This capacity was obtained from the nominal capacity by means of Peukert's equation.

duty [3–5]. Such operation is similar to that experienced in RAPS systems in that the battery is maintained below a full SoC for long periods of time, but the batteries are charged and discharged at very high rates (e.g., up to 100 times that experienced in RAPS operation)—so-called high-rate partial-state-of-charge (HRPSoC) duty. It has been found that HRPSoC duty leads to an accumulation of lead sulfate on the surfaces of negative plates. This situation reduces the rechargeability of the battery and, if allowed to reach a critical level, curtails battery life. Given these findings, it is likely that the mechanism affecting gel batteries under RAPS duty is related to that affecting AGM batteries under HEV duty.

Open-circuit voltage measurements taken after the completion of equalization at the end of the master cycle (step (iv), Section 3.2) have shown that the battery is below 100% SoC. Thus, in order to ensure that batteries are fully charged after each master cycle, the overcharge was increased during subsequent master cycles (see Table 1). Results show that 102% overcharge provides a good compromise between maintaining battery capacity and minimizing the potentially damaging effects of excessive overcharge/gassing. This level of overcharge has been used in all remaining testing and optimization.

4.2. PSoC window

The performance of the 24 V battery bank operated under simulated RAPS duty using PSoC windows of 47–72 and 40–65% SoC has been investigated. In this study, the chosen PSoC windows are of the same size (25% SoC) but have different upper and lower limits. Hence, the distinction between windows, referred to as 'higher' or 'lower', relates to the position of the mean SoC value. The results, in terms of voltage response, along with those already obtained for the 58–83% SoC window (included for comparative purposes) are shown in Fig. 5. The rate of increase in the ToCV as PSoC duty progresses is found to be higher at the higher PSoC windows. Interestingly, this behaviour has also been reported for AGM batteries operated under HEV duty [3,4].

The potentials of the positive- and negative-plate groups (versus a standard $Hg|Hg_2SO_4$ electrode) from two pilot cells within the 24-V string during the fifth (58–62% SoC), sixth (47–72% SoC) and seventh (40–65% SoC) master cycles (see Table 1) are shown in Figs. 6 and 7, respectively. There is no significant change in the potential of the positive plates throughout each of the three master cycles. By contrast, the potential of the negative plates for both pilot cells during master cycle five (58–83% SoC) gradually becomes more negative, i.e., from −1.0 to −1.4 V. This trend is much less obvious for the next lowest PSoC window (47–72% SoC, master cycle six), although the second pilot cell still displays a significant change within the last 4–5 days of the master cycle. At the lowest PSoC window (40–65% SoC, master cycle seven), the negative potentials of both pilot cells are very similar and change by less than 100 mV throughout the cycling period—this is approximately 25% of the change recorded at the highest PSoC window (i.e., 400 mV). Hence, operation at lower PSoC windows mitigates the problems associated with the ToCV of the negative plates. As a result, the number of PSoC cycles between full recharges could be increased, which would lead to an increase in the efficiency of the diesel generator. Further, cycling at lower SoCs has the added benefit of reducing gassing, grid corrosion and electrolyte dry-out. Nevertheless, this mode of operation requires careful consideration of the daily energy requirements, to avoid over-discharge of the battery bank.

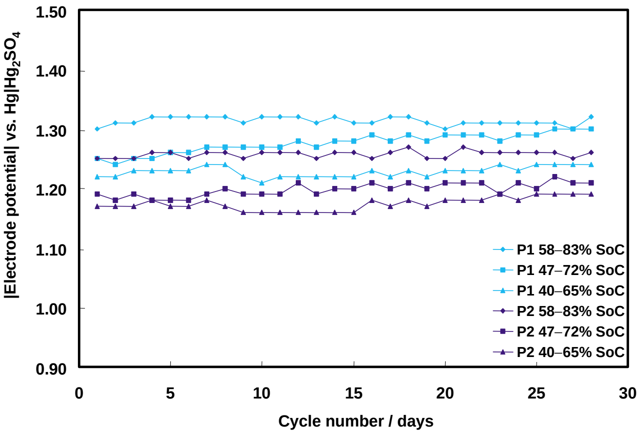

Fig. 6. Positive-plate potentials of pilot cells during master cycles five (58–83% SoC), six (47–72% SoC) and seven (40–65% SoC).

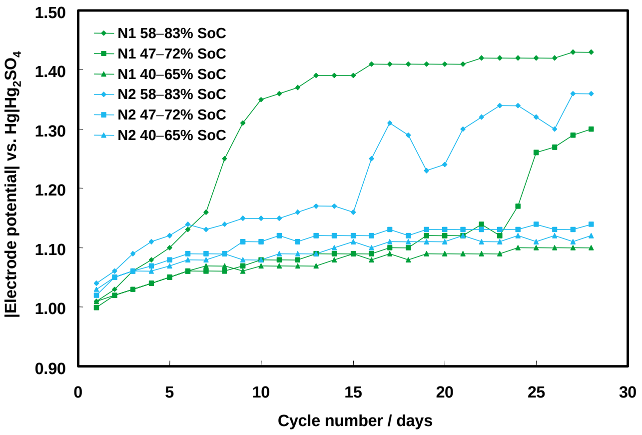

Fig. 7. Negative-plate potentials of pilot cells during master cycles five (58–83% SoC), six (47–72% SoC) and seven (40–65% SoC).

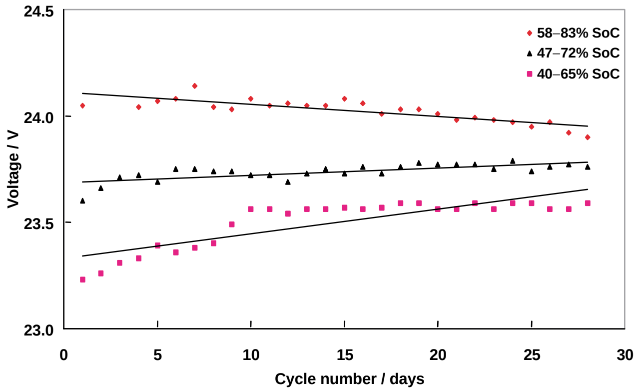

Fig. 8. EoDV during master cycles five (58–83% SoC), six (47–72% SoC), and seven (40–65% SoC).

The end-of-discharge voltage (EoDV) for each of the three master cycles is shown in Fig. 8. During master cycle five (58–83% SoC), the EoDV decreases gradually as the schedule progresses (Fig. 5). During master cycles six (47–72% SoC) and seven (40–65% SoC), however, the EoDV increases slightly during the first 10 PSoC cycles, before stabilizing for the reminder of the master cycle. This behaviour can be attributed to an improvement in charging efficiency at lower SoC windows. The initial increase in EoDV was not expected and is difficult to explain at this time. It is observed for all master cycles, albeit to a lesser degree for the 58–83% SoC window. Nevertheless, it is clear that the EoDV decreases only when the highest PSoC window is employed.

5. Summary and recommendations

In summary, the following recommendations have been made for battery management for the Padre Cocha RAPS facility.

- The battery bank should be operated for 28 days between full recharges, i.e., each master cycle should comprise 28 PSoC cycles.
- The PSoC window should be either 47–72 or 40–65% SoC.
- The equalization charge should comprise a charge with a voltage limit of 2.45 V per cell until 100% has been achieved, followed by a 10 A charge until 102% overcharge has been delivered.

It has been demonstrated that the behaviour of gel cells operated under extended RAPS PSoC duty is very similar to that shown by AGM units subjected to long-term HEV duty [3–5]. In both cases, the negative-plate potential shifts to more negative values as the PSoC duty progresses. By contrast, the positive-plate potential remains unaffected. Also, the change in the negative-plate potential on cycling decreases as the PSoC window is lowered. Given this similarity in behaviour, it is considered likely that a similar mechanism is responsible for the observed behaviour under the two forms of service. Preliminary studies have shown that using additional carbon in the negative plates [3,4,6,7] improves the performance of batteries operated under both RAPS and HEV operations. The exact mechanism responsible for the improvement, and the optimum type and concentration of carbon has yet to be determined. It is considered that such optimization would offer a large benefit in terms of extended battery life in RAPS systems.

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