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Benefits of partial-state-of-charge operation in remote-area power-supply systems

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Abstract

Many people throughout the world are remote from electricity networks and do not have access to reliable power. Remote-area power-supply (RAPS) systems offer a reliable and cost-effective alternative to grid connection. Achieving adequate performance from such systems requires appropriate componentry and well-designed control systems/strategies. A relatively new operating methodology—known as partial-state-of-charge (PSoC) operation—is now finding application in the field. The strategy, which can give a three-fold increase in the lifetime energy-delivery of gelled-electrolyte batteries compared with that obtained using traditional charging procedures, is to be employed in RAPS systems in Peru. The PSoC algorithms will be formulated and trailed in the laboratory, and then installed in the Peru facilities where they will be monitored and controlled remotely via a satellite link-up. This approach allows the algorithms to be fine-tuned in situ, and will ensure that system efficiency and battery lifetime are maximised. Use of the PSoC concept is expected to provide a battery lifetime of 8 years.

Keywords: Control system; Lead–acid battery; Partial-state-of-charge; Peru; Power supply; Remote area

1. The need for remote-area power supplies

Over two billion people living in developing countries do not have access to adequate electricity supplies [1–3]. Generally, this is the result of (i) the isolated and fragmented geography of many of the countries (the Philippines, for instance, consists of over 7000 islands); (ii) the high cost of installing and maintaining large-scale electrification networks [4]. Where mains grids have been established, the power supply is frequently unreliable and of poor quality. Further, the upgrading and extension of a grid can often be beyond the financial capabilities of a country. Many developing nations have abundant supplies of renewable energy from the sun and/or wind. Hence, the wide-scale deployment of remote-area power-supply (RAPS) systems that incorporate renewable energy can be a cost-effective alternative to large-scale mains grids [5].

Such systems also provide power for applications other than households and communities. These include (i) telecommunications; (ii) water pumping; (iii) emergency lighting; (iv) sign lighting; (v) cathodic protection; (vi) navigational aids; (vii) vaccine refrigerators; (viii) electric fences. The facilities may be sited on oceans and mountains, or in areas within existing electricity networks where stand-alone power systems are more cost-effective than grid extensions. A good example of the latter is freeway lighting, for which the installation of a RAPS system can avoid the expensive process of running power cables underground.

2. Design and components of RAPS systems

To supply continuous power, RAPS systems must have either a diesel generator in constant operation or a battery bank. If renewable energy is abundant, RAPS systems can also include a photovoltaic (PV) array, a wind generator, and/or a hydroelectric generator. An inverter to convert direct current (dc) to alternating current (ac) is also a common component in many facilities. Further, all RAPS systems must have a control strategy and management system to regulate power flow and to operate the system at an acceptable level of efficiency.

Various factors are used to determine the optimum system topology for a given facility, namely, (i) power and energy required; (ii) availability of renewable energy; (iii) cost of generator operation and system maintenance; (iv) site accessibility; (v) available finance. The basic layout of most RAPS systems is, however, similar (see Fig. 1).

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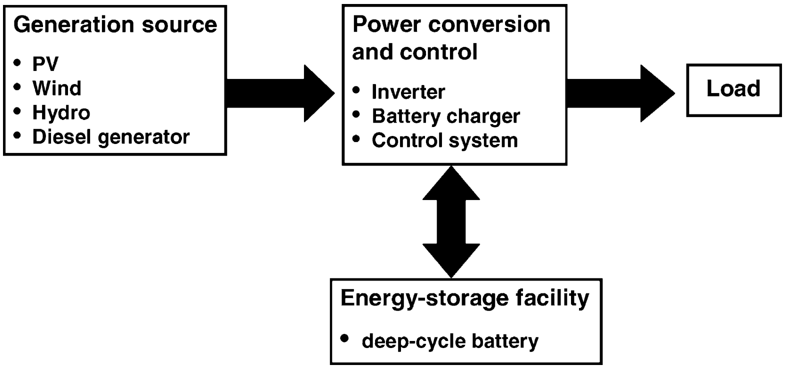

Fig. 1. Typical design of a RAPS system.

2.1. Battery bank

To date, three different types of rechargeable batteries have been employed for energy storage in RAPS facilities, viz. nickel–cadmium, nickel–iron, and lead–acid. Nickel–cadmium units have excellent service lives and high resistance to abuse, but are disadvantaged through low charging efficiency, high cost, appreciable self-discharge, excessive water consumption (vented design only), and environmental concerns. Several countries have already enforced strict regulations for the disposal of spent nickel–cadmium batteries. Nickel–iron batteries also suffer from high self-discharge, high water consumption, and low charging efficiency. By contrast, the lead–acid battery has gained wide-scale acceptance in RAPS applications, and is still the most efficient and cost-effective option for the majority of situations. Also, lead–acid batteries are approximately one-quarter the price of their nickel-based counterparts, and in most countries there is an effective infrastructure for the distribution, servicing and recycling of the batteries.

2.2. Diesel generator

Diesel generators are the primary energy source for many RAPS systems. Such units consist of an internal combustion engine (fuelled by diesel oil) and an alternator that produces ac power. Generators that deliver dc power have also been used, but are no longer common as they are not as efficient as their ac counterparts. Petrol generators can also be employed for RAPS duty, but they have greater maintenance requirements and are more expensive to operate. To obtain the best possible fuel efficiency from small (<12 kW) diesel generators and to minimise maintenance requirements, the load factor should be kept above 60–70%.

2.3. Photovoltaic array

A solar cell converts energy from the sun directly into electricity. A group of these cells (usually 36) connected in series, with a protective backing and covering, is referred to as a PV panel or module. When these panels or modules are grouped together, they are referred to as a PV array. Generally, PV modules have an operating voltage of 12 V and power outputs that range from 25 to 75 W. The panels can be arranged in a series and/or parallel configuration to provide the required operating voltage and current. For optimum efficiency, the modules must be correctly orientated with respect to the sun. Maximum power-point trackers can be used to increase the performance of PV-based facilities. These devices are basically dc to dc converters, and are placed between the PV array and its load. The concept is based on the principal that maximum power is obtained at a particular voltage which varies with array temperature. Hence, by ‘sampling’ or ‘tracking’ the PV array voltage and modifying it accordingly, power to the load can be maximised. It is common for increases in efficiency of 10–15% to be realised in systems that are capable of producing from 3 to 5 kWh per day.

2.4. Wind generator

There are two main designs of wind generators, namely, vertical- and horizontal-axis machines. The former technology is more suited to high-wind conditions and has the advantage of being serviceable from the ground. Horizontal-axis turbines, however, are more efficient at lower wind speeds and are more widely accepted and used. These units are available in two configurations. One version has the turbine blades on the upwind side of the generator and tower, while the other has the blades situated downwind. The most common wind generators used in RAPS system are in the 0.25–50 kW range. The site for a wind generator is critical if it is to provide satisfactory performance. In fact, the location is more important than in the case of PV arrays, as considerable variations in wind speed can occur from one site to another, particularly in mountainous and wooded areas. An acceptable site should be free of obstructions such as trees, hills, buildings and other wind generators. Ideally, the wind speed at prospective locations should be monitored for a period of up to 2 years to ensure that the wind regime is consistent and reliable.

2.5. Hydroelectric generator

Hydroelectric generators can provide a continuous supply of energy, given a reasonably consistent flow of water from a nearby stream or river. In practice, however, hydro-based RAPS facilities for domestic use often have small battery banks to provide additional power during peak periods, i.e. for load levelling or peak shaving. Smaller generators commonly produce between 10 and 30 kWh per day and, once installed, require minimal maintenance. Although the capital cost of a hydro system can be high, such facilities can produce energy more cheaply than a PV array. This is because the price per installed kW decreases with increasing system size. For example, upgrading a 1 kW generator to a 2 kW unit may only increase the initial capital cost of the system by 30%.

2.6. Inverter

Inverters are employed to convert dc drawn from battery banks to ac. Traditionally, either square-wave or modified square-wave inverters have been used in RAPS systems. Although such units are relatively crude and offer a poor approximation of the ac sine-wave, they are inexpensive and, hence, still find application in small RAPS systems. The inverters can, however, give rise to background noise in hi-fi equipment, as well as cause operational problems with electric motors, fluorescent lights, radios, televisions, microwave ovens, and computers.

Modern inverters installed in RAPS systems are called ‘sine-wave’ inverters and, as their name suggests, produce sine-wave power. These devices deliver high quality power and can be used to operate even the most sensitive electrical equipment. Sine-wave inverters are very efficient (>95%) and have proven to be very rugged and reliable. Bi-directional sine-wave inverters are also available. These devices have inputs for renewable energy and can act as a battery charger. In addition, they can synchronise with any ac signal (i.e. the output from external ac sources and the inverter are additive), are microprocessor controlled, and can utilise advanced charge–discharge algorithms to optimise system operation.

2.7. Control system

An effective control system is required both to ensure that the RAPS facility operates at an acceptable efficiency, and to guarantee the longevity of components. Control systems vary significantly in complexity.

The simplest controllers used in RAPS system are those that regulate small PV-battery hybrid systems. Such units may impose the following: (i) a top-of-charge-voltage (ToCV) limit; (ii) a low-voltage disconnect set point; (iii) a load reconnect voltage value. There are two common designs for these controllers or regulators, i.e. shunt or series types. These designs can be further sub-divided into ‘linear’ or ‘switching’ types. The linear mode provides a ‘true’ constant-voltage charging regime, whereas the switching mode involves ‘interrupting’ or ‘chopping’ the PV current. Although switching strategies possess the advantage of not requiring additional componentry to allow the dissipation of energy in the form of heat, they do have charging hystereses. This can lead to a ‘quasi’ partial-state-of-charge cycling rather than constant-voltage duty. Recent advances in electronics have led to the development of controllers based on pulse–width-modulation techniques. These devices produce a much smaller charging hysteresis and, as a consequence, are the preferred option for small-scale controllers.

For medium-to-large RAPS facilities that have multi-energy inputs, more sophisticated control strategies are employed. Microprocessor-based units that record and utilise many different parameters (such as those used in bi-directional inverter/battery hybrid systems) offer the most accurate control. These devices can monitor/calculate variables such as battery voltages, string currents, battery temperatures, ambient temperatures, battery bank state-of-charge (SoC), and overcharge delivered. Such devices are recommended for use with all RAPS systems that use valve-regulated lead–acid (VRLA) batteries, as the latter require carefully controlled charging to deliver a satisfactory performance.

3. Importance of effective control strategies for RAPS systems

3.1. Traditional charging procedures

Traditional charging procedures employed for VRLA battery banks in RAPS systems have generally been based on algorithms used for flooded-electrolyte systems, but with a reduced ToCV limit (typically 2.3–2.4 V/cell compared with 2.5–2.6 V/cell). The strategies usually comprised an initial constant-current charge followed by a period at constant voltage. Where practical, a periodic boost charge was often provided to ensure that the batteries were fully recharged (note, the VRLA technology requires a lower ToCV level due to the oxygen-recombination process that is active within the batteries).

Shortcomings associated with the use of constant-current–constant-voltage strategies become obvious when the time required to charge fully VRLA batteries from a low SoC is considered—this time can exceed 24 h for new units. Obviously, most RAPS systems are unable to provide such extended charge times, especially PV-based facilities. To complicate the issue, VRLA batteries experience gradual electrolyte dryout as they are cycled. This, in turn, causes an increase in both the size and number of pathways available for oxygen transport to the negative plates. As a result, the maximum possible rate of oxygen recombination increases, the float current for a given ToCV increases, and more overcharge is required to bring the battery to full charge (note, this behaviour is exacerbated by changes in temperature). Despite the need for more overcharge, the charging time generally decreases. Typically, an 'aged' VRLA RAPS battery can be fully recharged from a low SoC in as little as 6 h.

Many of the problems related to constant-voltage charging can be avoided by completing the charging process with a period of constant current, i.e. a so-called constant-current–constant-voltage–constant-current charge. This approach can deliver an accurate level of overcharge, and thereby reduce the possibility of excessive dryout and corrosion. A variation to this approach is to use a constant current until recombination has commenced (i.e. ~2.45–2.5 V/cell), then charge at a lower value of constant current until a pre-set change in voltage (dV/dt) has been reached. Obviously, both these strategies require a reliable charge return and, therefore, are best suited for use in systems that incorporate a diesel generator. They can still be used in PV-only RAPS systems, but a more sophisticated control strategy is required to ensure that batteries receive a regular full recharge.

3.2. Partial-state-of-charge (PSoC) operation

An operating strategy that is gaining favour with RAPS designers is called partial-state-of-charge (PSoC) operation. It is useful for batteries that are resistant to electrolyte stratification (e.g. gelled-electrolyte designs) and operates the battery below a full SoC for extended periods of time with infrequent, but thorough, equalisation/boost charges (note, the procedure can also be used with flooded-electrolyte batteries, provided that they are fitted with a system to remove acid stratification). PSoC operating strategies generally comprise the following three regimes (Fig. 2):

- Regime 1: a discharge to ~20–50% SoC;
- Regime 2: a charge to ~70–90% SoC, followed by a discharge to ~20–30% SoC);
- Regime 3: an infrequent, but regular and thorough conditioning charge.

Regime 1 involves an initial discharge to ~20–50% SoC. In Regime 2, the battery is cycled within a fixed SoC operating window until a pre-set number of charge–discharge cycles (called PSoC cycles) have been completed. A conditioning charge, referred to as Regime 3, is then applied. This procedure often comprises a constant-current–constant-voltage–constant-current charge operation, and is required to correct imbalances that may occur between negative and positive plates, and between cells in series, as a result of variations in charging efficiency. Conditioning is also beneficial in terms of minimising the formation of so-called 'hard sulphate' (i.e. lead sulphate that becomes difficult to recharge).

The required frequency, time and intensity of the recovery procedure may vary from weeks to months and depends upon the cycling history of the battery. For example, batteries charged at low rates tend to operate at high charging efficiencies due to a low level of gassing. Higher charge rates increase the level of gassing and, as a consequence, increase the likelihood of plate per cell imbalances occurring within batteries. Hence, batteries charged at high rates generally require a more frequent recovery than those operated with lower rates. The charging efficiency of batteries also

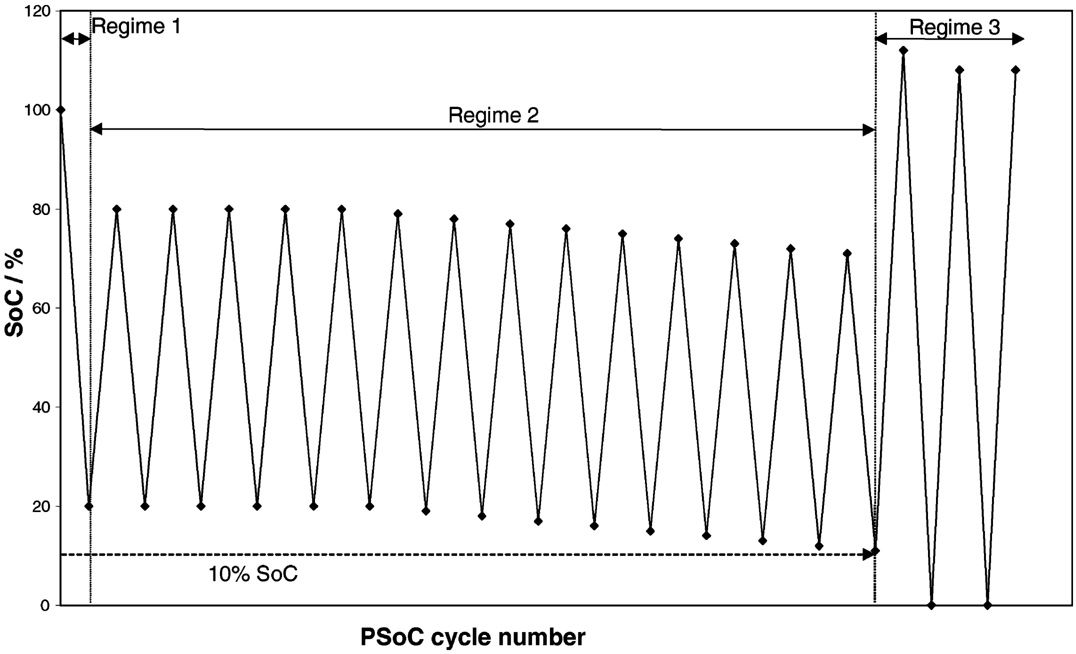

Fig. 2. Schematic representation of PSoC operating procedure.

decreases with increasing SoC. For example, a unit operated within a PSoC window of 30–70% SoC will provide a higher charge efficiency than a battery cycled between 50 and 90% SoC. As a consequence, the latter battery will require a more frequent recovery than the former.

The first reported long-term study on PSoC duty [6] involved operation of a gelled-electrolyte battery between 40 and 70% SoC for a total of 5500 discharge–charge cycles, with a full recharge and capacity test every 84 PSoC cycles. The capacity of the battery at the completion of testing was still 95% of the nominal value. The energy delivered by the battery during its lifetime was equivalent to that obtained from 1650 cycles to 100% DoD. Also, only 14 Ah of overcharge were delivered every 84 PSoC cycles, giving an overall charging efficiency of above 99%. The longevity of the battery was attributed to the low level of overcharge, which reduces electrolyte dryout, corrosion of the positive grids and other damage to the positive active-material during charge. A second paper [7] reports data for a novel form of gelled-electrolyte battery which was operated continuously between 60 and 90% SoC with a boost charge every 100 cycles. The capacity of the battery was still above 80% of the nominal value after 6000 cycles. The energy delivered by this battery was equivalent to that obtained from 1800 cycles to 100% DoD.

The use of PSoC algorithms in RAPS systems has very important practical implications. Not only does PSoC operation have the potential to increase both the lifetime energy of batteries in RAPS facilities, but it can also improve the overall operating efficiency of systems, especially those with diesel generators. In the latter case, the improvement is a direct result of a reduction in the diesel runtime at low loads.

Practical benefits of PSoC operation are demonstrated by the following example. Battery banks in a well designed, traditional RAPS systems are often discharged to between 50 and 60% SoC on a daily basis. They are then usually recharged using a constant-current–constant-voltage regime, with charging generally extended for at least 0.5 h after a voltage limit has been reached. The charging process, which typically increases the SoC to above 90% SoC, can take over 3 h, although this can vary depending upon the size of the diesel generator. Further, battery banks in such systems are usually given a weekly regular boost charge which can require up to 6 h for completion, depending upon the type, age and condition of the battery. The run time of the diesel generator over a 7-day period is, therefore, 27 h. On the other hand, modelling of RAPS systems based on PSoC operating procedures has shown that the daily diesel runtime could be reduced to ~2.5 h per day for a 40–70% SoC operating window. Under this strategy, charging is terminated as the ToCV limit is reached and thereby maximises the operating efficiency of the diesel generator. Also, if a boost charge is provided every 36 daily cycles (which is considered a conservative strategy based on the data presented above, i.e. 5500 cycles for a PSoC window of 40–70%, with equalisation every 72 cycles), it is easy to calculate that the average diesel runtime for a 7-day period would be ~19 h. This is 30% less than that expected using traditional strategies (i.e. 27 h, see above).

4. RAPS systems for Peru—demonstration of benefits of PSoC operation

The practical benefits of PSoC operation are to be demonstrated in a project based in the Amazon region of Peru. The programme involves the installation and demonstration of a series of RAPS facilities that utilise PSoC operating strategies. The major objective of the project is to demonstrate the efficacy of using non-grid, clean, inexpensive electricity on a village-wide basis. The use of PSoC duty is expected to extend battery life to 8 years as well as to improve system efficiency and to reduce fuel consumption and related pollution.

The Peru initiative was instigated in 1997 by the government of Peru, the International Lead Zinc Research Organisation (ILZRO), the Solar Energy Industries Association (SEIA), and several international companies and research groups. Funding for the programme comes from the United Nations Development Program and other national and international energy, environmental and developmental organisations and agencies.

4.1. Configuration of RAPS systems

Initially, RAPS systems will be installed in two villages in the Loreta area, namely, Padre Cocha and Indiana. The communities already have diesel generators and a rudimentary electric grid, but they do not have 24 h power. Also, the generators operate inefficiently and require appreciable maintenance. Installation of a system that comprises diesel generators, a PV array and a VRLA battery bank will provide highly reliable, 24 h power.

The design of the system is based on 150 kWh modules (Fig. 3). Each module comprises the following: (i) a 15 kW PV array; (ii) a 50 kW inverter; (iii) a 50 kW diesel generator; (iv) two, 240 V strings of lead–acid batteries (total of 750 Ah at the 10 h rate). The village of Padre Cocha will have two modules which will provide 300 kWh of power (Fig. 2); Indiana will have four modules. The design of the system is such that a third string of batteries and/or additional PV capacity can be added to each 150 kWh module, if required.

The batteries chosen for the project are of the gelled-electrolyte variety and have been especially designed by CSIRO and Battery Energy Power Solutions (BEPS) for high-temperature, deep-cycle RAPS applications [8]. The batteries, called 'SunGel', have thick positive plates (5.5 mm) and are capable of over 1100 cycles (100% depth-of-discharge). Also, the operating efficiency of the batteries is superior to that of comparable technologies, due to the use of an ultra-pure form of lead developed by

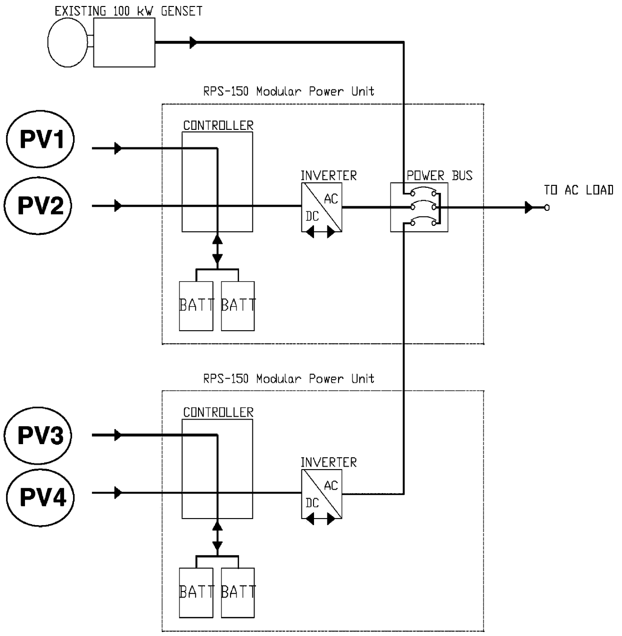

Fig. 3. Configuration of RAPS system at Padre Cocha.

Pasminco and CSIRO, 'VRLA Refined^{TM} lead' [9]. Further, the batteries can be manufactured at a moderate cost due to several proprietary manufacturing processes.

The RAPS systems in Peru will be operated and monitored remotely using algorithms designed specifically for the project. The PSoC strategies will be developed and evaluated in the laboratory by CSIRO (see Section 4.2, below), and then refined and optimised in the field.

4.2. Algorithm development

In order to maximise the benefits associated with PSoC operation, the SoC operating window (e.g. 40–70 or 50–80% SoC), the number of PSoC cycles performed between recovery charges, and the recovery charge itself should be optimised.

4.2.1. SoC operating window

The top limit of an SoC window should be as low as practicable so as to minimise gassing and corrosion. On the other hand, the limit should be sufficiently high to avoid overdischarge of the battery during periods of high energy demand.

The derivation of an appropriate SoC operating window first requires the formulation of a simulated discharge profile. Such profiles are preferably based on data obtained from a comparable system, or from a careful study of information supplied by the potential RAPS customer. The discharge profile is then combined with an expected charging pattern (both solar- and diesel-based) to produce an overall 'power profile'. This procedure has been performed for the Padre Cocha RAPS site; the power profile is shown in Fig. 4. An overall PSoC operating window is then formulated, based on this power profile and consideration of the following: (i) design of the proposed battery (e.g. capacity, charge-acceptance, charge efficiency); (ii) the availability of full recovery charging; (iii) required system efficiency; (iv) proposed operating time of the diesel generator (if included).

4.2.2. Number of PSoC cycles

Operating batteries for the optimum number of PSoC cycles between full recharges (called $\mathrm{PSoC}_{\mathrm{optimal}}$) is important if a suitable compromise between system performance and battery cycle-life is to be achieved. The $\mathrm{PSoC}_{\mathrm{optimal}}$ is derived from the maximum number of PSoC cycles that can be performed before a full recovery is required (termed $\mathrm{PSoC}_{\mathrm{max}}$). The latter is obtained by operating a 'dummy' battery bank in the laboratory under the simulated power profile and the selected SoC operating window (see Section 4.2.1) until battery performance starts to decrease. As a

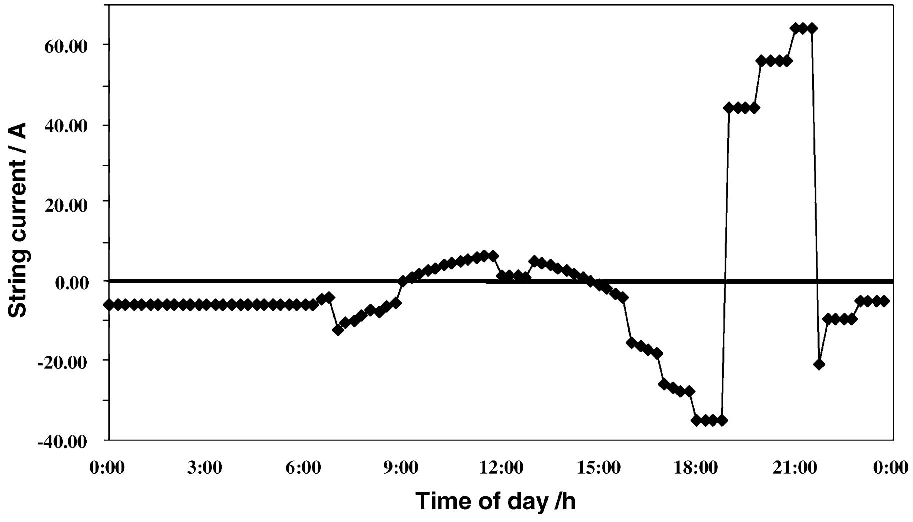

Fig. 4. Simulated 24 h power profile for Padre Cocha RAPS site.

guide, in a conservative PSoC strategy, the $\mathrm{PSoC}_{\mathrm{optimal}}$ is normally $\leq 0.5\ \mathrm{PSoC}_{\mathrm{max}}$.

4.2.3. Recovery procedure

The last step in the development of a PSoC strategy is to optimise the regular recovery procedure that is required to maintain battery capacity. This is achieved by first operating a battery under PSoC duty until the unit requires recovery, and then recharging the battery with what is considered to be a 'more than adequate' level of overcharge. This process is then repeated with a gradually decreasing level of overcharge, until the recovery procedure no longer returns the batteries to a full SoC. The overcharge delivered at this point is then considered to be the minimum that should be delivered to maintain battery capacity.

4.2.4. Laboratory evaluation and fine-tuning

PSoC strategies should be evaluated and fine-tuned in the laboratory using a dummy battery bank before being implemented in the field. For new applications where PSoC operating strategies have not previously been developed, it is preferable to monitor the performance of the system and then fine-tune the algorithm in situ. In the case of the Padre Cocha RAPS site, the system can be monitored and controlled remotely using a satellite connection. If required, this provision will allow fine-tuning of the algorithm throughout the life of the system, and should reduce the frequency of site visits to an absolute minimum (i.e. for routine diesel generator maintenance).

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