A RECOMMENDED PRACTICE FOR REPLICATING THE PADRE COCHA SUCCESS
(DRAFT PeruStd[2].doc)
(Jan. 19, 2004)

1.0 Introduction

A small, electrical power system that provided electricity to the remote community of Padre Cocha, Peru for a few hours each evening has been converted or upgraded to the status of a hybrid remote-area power supply (RAPS). The hybrid RAPS provides a host of quality-of-life enhancements to the community via continuous access to an increased quantity of electrical energy. A portion of the energy from the hybrid RAPS is from a photovoltaic (PV) array. The diesel-powered generator, which still operates for only a few hours each day, operates under more efficient circumstances, and the energy-storage batteries buffer both energy and power demands. As the hybrid RAPS continues to provide continuous access to electrical energy at Padre Cocha, it is anticipated that its success will engender a growing demand for similar systems in many other remote Peruvian communities, a trend that is already evident. This document addresses that issue as well as a future operating strategy for the Padre Cocha system.

2.0 Purpose and scope

The purpose of this document is to recommend an optimum approach to implementing hybrid RAPS systems in remote areas of Peru. In particular, a partial state-of-charge (PSoC) operating practice is recommended for the hybrid RAPS at Padre Cocha and for subsequent conversions as well. This strategy will enhance the life and performance of the RAPS battery by dramatically reducing the number of equalization charges and, thus, the potential of venting via the cells' regulation valves. It essentially requires, however, that the battery be a gel-type, VRLA battery, because the gel battery is not subject to electrolyte stratification. Additionally, the recommended strategy will operate the battery in a PSoC window that maximizes both battery charge efficiency and, concurrently, generator operating efficiency. Departures from these advantageous circumstances are limited to the infrequent equalization charges that are recommended at twenty-eight day intervals.

It is also recommended that subsequent hybrid RAPS conversions or installations in Peru be implemented using only qualified components, i.e., components that have been demonstrated to perform successfully in hybrid RAPS systems. In this regard, it is further recommended that the components used in the Padre Cocha hybrid RAPS, both original components (perhaps with modifications) and added components, be defined as qualified components. The Padre Cocha hybrid RAPS is performing well. While only time and performance can prove a system's value and reliability, the Padre Cocha system is off to a great start, and it is anticipated that it will continue to meet expectations throughout its 20-year design life.

The scope of this recommended practice is limited to the implementation of hybrid RAPS systems for remote, Peruvian villages that lack a continuous supply of electricity. These villages will likely, but not necessarily, have an existing electrical distribution system powered by an engine-driven (e.g., diesel) generator that provides electricity for only a few hours each day.

3.0 Background

Figure 1 is a schematic diagram of the hybrid RAPS installation in Padre Cocha, Peru. In the original power system, the 100-kW diesel generator output was supplied directly to the 0.38- to 22.9-kV step-up transformer for distribution and subsequently to the four step-down transformers serving community loads. Converting the system to a hybrid RAPS involved the addition of the two RPS-150 modules between the generator and the distribution system. These two RPS-150 modules normally operate in parallel via synchronization of the two inverters, however, either can be isolated for repair or maintenance while the other module continues to support the system. Each of the RPS-150 modules establishes a 240-V d.c. bus that is supplied by the diesel generator via a rectifier, a 240-V PV array and a 240-V battery. With the addition of either or both of the RPS-150 modules, the Padre Cocha system meets the definition of a hybrid RAPS. It integrates renewable and dispatchable generators, a battery for energy storage, and necessary controls to supply a remote electrical load.

Hybrid RAPS systems are advantaged by the complementary nature of their distinctly different generators. They are relatively independent of renewable resource (solar) cycles, and their battery-charging options are relatively unconstrained. Hybrid systems' reliability, fuel requirements, and loss-of-load probability all benefit from the dual generation option. They moderate the relatively high initial cost per watt of renewable generation and the relatively high operating cost of dispatchable generation. Typically, hybrid systems require more maintenance than renewable-only systems and less generator maintenance than dispatchable-only systems because their generators operate under more optimum conditions.

Prior to the conversion of the Padre Cocha power system to a hybrid RAPS, the cost of generating electricity included the costs of supplying diesel fuel to the remote location and diesel engine maintenance, which tended to be high because the diesel usually operated at relatively inefficient, low-load conditions. Operating the diesel only a few hours each day effectively capped fuel cost by restricting access to electricity. It also concentrated the electrical load by restricting the time loads could be operated. Nevertheless, diesel loading was usually too low for efficient diesel operation. In the converted system, the PV arrays provide additional energy (≈ 300 kWh daily), and the batteries provide the essential buffering between power and energy availability and the village load. Notably, the diesel is still operated only a few hours each day and under more favorable load conditions. A brief description of the evolution of the hybrid RAPS at Padre Cocha is included in Annex A.

4.0 Recommendations

4.1 Safety considerations

Hybrid RAPS systems should be isolated from casual contact such that only authorized personnel will have access to system components. Power outlets and connected loads at consumer sites are, of necessity, readily accessible, and these outlets and connections should conform to local codes and practices. Authorized repair, maintenance and service personnel should be trained, qualified and familiar with mechanical, electrical and other hazards associated with hybrid RAPS systems. Annex B contains an informative discussion of electrical safety issues. Concerns relevant to ventilation issues are circumvented by the use of VRLA batteries.

4.2 Qualified components

In the interest of achieving safe, economic, and reliable service from these hybrid RAPS systems, it is recommended that only components qualified via demonstrated performance or testing be used in such systems. In this regard, it is recommended that the components used in the Padre Cocha hybrid RAPS system be designated qualified components by virtue of their performance to date. Additional components can be qualified via a similar route. Only time in service or reliability testing, which is a highly specialized technology, can demonstrate or quantify a level of reliability. For the present, components of the Padre Cocha system were carefully chosen and have demonstrated some level of reliability by continuing to perform well. Subsequent paragraphs discuss specific components.

4.2.1 Engine-powered generators

It is anticipated that most Peruvian villages scheduled for power-system upgrades similar to the Padre Cocha hybrid RAPS experience will incorporate an existing diesel-powered generator into the converted system. It is recommended that such generators be qualified via comparison with the Padre Cocha diesel-powered generator, which was modified by the addition of a three-phase capacitor network or filter to the generator output. The affect of the added capacitive filter has not been quantified, but it certainly reduced the harmonic content of the output and also reduced any noise on the remaining 60-Hz sinusoidal voltage. It is also important that the generator output voltage and frequency be well regulated. These parameters appear to be entirely satisfactory in the Padre Cocha hybrid system. It is recommended that the output of the Padre Cocha generator be measured at the output of the added capacitive filter under low, medium and high load conditions, and that these measurements become the basis for qualifying generators for other conversions. These generators, too, may require the addition of capacitive filtering in order to become qualified.

For villages that do not have an existing generator, it is recommended that a suitable generator be selected and qualified on the basis of specifications or test results that demonstrated performances that match or exceed the performances of the Padre Cocha generator. This should be done with a view toward using the generator in multiple other similar systems.

The basic qualification measurements should include phase and line voltage balances, voltage and frequency regulation, harmonic content of the filtered output, and a quantitative assessment of power factors, which should be reasonably high. Power factors less than 75% should be considered suspect and the reason for the low values investigated. Some of these observations may require instruments that are not readily available. Measuring total harmonic distortion, for example, requires a specialized instrument that may not be readily available. The objective of these measurements or observations is to provide at least a qualitative evaluation of the generator, which should meet or exceed the performance of the Padre Cocha generator, as modified, for qualification purposes.

4.2.2 The battery

4.2.2.1 Battery selection

It is recommended that the battery be a gel-type, VRLA battery that features an ultra-pure form of lead and thick positive plates (≈ 5.5 mm). The following section recommends a partial-state-of-charge (PSoC) operating strategy, which essentially requires that a gel VRLA battery be specified.

It is also recommended that the "SunGel" battery used in the Padre Cocha hybrid RAPS be designated a qualified battery because of its design features and results of a special study and evaluation of this particular battery [1]. The results of this study are discussed in the following section.

Under most circumstances, vented and VRLA lead-acid batteries share a common, familiar electrochemistry. Under charging conditions that result in the electrolysis water in the electrolyte, which produces hydrogen and oxygen, VRLA cells, by design, feature a "recombination cycle", which limits the escape of these gasses to the atmosphere and promotes their recombination to water and its return to the electrolyte. Concurrently, this design feature also prevents the infusion of atmospheric oxygen into the VRLA cell, which, otherwise, would be detrimental. There are several advantages inherent in the VRLA cell's "valve regulated" feature. Compared to their vented counterparts, VRLA cells do not require electrolyte maintenance (i.e., the addition of water), they are less voluminous and weigh less (greater specific energy) and are not constrained to a vertical orientation. Moreover, they are more rugged and easier to transport and interconnect. A particularly advantageous result is that VRLA cells, and especially gel-types, are not subject to electrolyte stratification. Thus, gel-VRLA batteries can be operated for long periods of time in a PSoC without equalization charges. This attribute is especially advantageous in hybrid RAPS duty.

4.2.2.2 Battery management

Newnham and Baldsing conducted an extensive study and experimental evaluation of the SunGel battery and developed an operating strategy for the battery in hybrid RAPS application such as the Padra Cocha application [1]. They note the critical importance of the battery to the success of a hybrid RAPS, and they comment on features of the SunGel battery that make it a preferred choice for the hybrid RAPS application. These features include the use of an ultra-pure form of lead in the battery and thick positive plates (5.5 mm). They also note that the

SunGel is produced at a competitive cost due to several proprietary-manufacturing processes.

Based on their study and experimental evaluation, Newnham and Baldsing made the following recommendations for managing the Padre Cocha hybrid RAPS [1]:

1) That the hybrid RAPS battery be operated for 28 days between full recharges, i.e., that the master cycle consist of 28 daily PSoC cycles followed by an equalization charge.

2) That the PSoC window be either 47 to 72% or 40 to 65% of rated battery capacity.

3) That after the 28 daily PSoC charges, the subsequent equalization charge consist of a full charge to a voltage limit of 2.45-V per cell until 100% of the discharged Ah(s) have been returned, followed by a 10A charge until 102% of the discharged Ah(s) have been returned.

It is recommended here that the Newnham and Baldsing recommendations listed above be accepted as the operating strategy for the Padre Cocha hybrid RAPS system and for other remote systems in Peru that undergo a similar conversion. The preceding recommendation that the SunGel battery be designated a qualified battery for the purposes of this document is based, in part, on the results and recommendations of their study. The SunGel battery, used within the constraints of these recommendations, should provide a service life of more than 8-years.

4.2.3 Photovoltaics

Single junction, single- or poly-crystalline photovoltaic (PV) modules are a mature, reliable and economic choice for PV arrays, and these are recommended here for the hybrid RAPS application. This recommendation is consistent with the PV array used in the RPS-150 modules at Padre Cocha.

4.2.4 Power electronics

Electronic components used within the constraints of their specifications (i.e., voltages, currents, temperatures, and power) are expected to perform to their specifications for long periods. In recent years, obsolescence rather than failure has tended to limit the life of electronic components. In hybrid RAPS systems, batteries are the more likely components to fail and, further, batteries are likely to be the more costly component on a life-cycle basis. Nevertheless, it is important that suitable electronic components be selected and qualified for the hybrid RAPS systems.

Rather than qualify individual components, it is advantageous to qualify electronics at a higher level, e.g., at the circuit, plug-in card, or module level. It is recommended here that the entire RPS-150 module used in the Padre Cocha RAPS be qualified by virtue of its design and performance in that application. The RPS-150 module has a convenient capacity with parameters that are suitable for many hybrid RAPS applications. Its capacity can be incremented so as to be suitable for a host other hybrid systems by adding or removing RPS-150 modules. Individual modules can be added to the parallel Padre Cocha configuration, for example, simply by causing the individual modules to operate in synchronism (via a common control signal). They can also be removed via a simply disconnection.

4.3 Standardization

Requiring the use of qualified components or subsystems (e.g., the SunGel battery or the RPS-150 module) imposes a reasonable level of standardization without being too restrictive. The standardization that is imposed via using only qualified components should result in better quality, more reliable systems. It will minimize the number of design decisions required to implement additional systems and also the potential of making poor component choices. It will also reduce the cost stocking spares. A mechanism can be defined to qualify additional components, e.g., demonstrated performance in hybrid RAPS service.

5.0 Preliminary assessment-documentation

A reasonably definitive description of an existing system selected for conversion to a hybrid RAPS would be very advantageous. Ideally, system documentation would include schematics, wiring diagrams and specifications of the existing major components. A record or history of the system's performances, including failures, maintenance, modifications would also be helpful. A lack of such records, however, is not a major issue and can be circumvented. A system's current status can be evaluated by observing measurable parameters, e.g., voltages, currents, power levels, power factors, wave forms, harmonics, etc., for a range of operating conditions. The objectives of these observations include evaluations of system balance, voltage regulation, phase relationships, and load balances. These observations or measurements will require a basic set of instrumentation, e.g., voltmeter, ammeter, wattmeter, and oscilloscope. Some of these measurement or observation capabilities are available in convenient, battery-powered combinations, e.g., multimeters and power-quality instruments. A basic set of instrumentation should be made available to personnel evaluating, converting, maintaining and trouble-shooting hybrid RAPS systems.

The Padre Cocha experience indicates that the output of an existing generator, especially, be evaluated. The output voltage of the generator, including transient excursions from the norm, and the input window of the electronics that the generator drives must be compatible.

6.0 References

[1] Newnham, R.H. and Baldsing, W.G.A., Advanced management Strategies for Remote-area Power-supply Systems, (To be published)

ANNEX A

A Brief Description of the Padre Cocha Hybrid RAPS Experience

Padre Cocha is a small, remote village in the Amazon region of Peru. Prior to installation of the hybrid RAPS in 2003, the village had a diesel-powered, 100-kW generator and a three-phase distribution system that provided electricity throughout the community for about 6-h each evening. The generator output, 240/415 VAC at 60 Hz, was routed, via a three-phase circuit breaker, to a 125-kVA, 0.24/22.9 kV, step-up transformer and subsequently distributed to four distribution transformers that stepped the voltage back to 240 VAC for powering community loads. One distribution transformer was rated 100 kVA; the other three were rated 50 kVA each.

The initial or existing Padre Cocha electric power system was subsequently converted to a hybrid RAPS by inserting two, paralleled, RPS-150 modules into the initial system. Fig. A.1 is a schematic of the hybrid system. As illustrated in Fig. A.1, each inserted RPS-150 module includes a charger module that rectifies the generator output to 240 VDC and, thus, establishes a 240-VDC bus. The DC bus feeds a 50-kVA, three-phase, 60-Hz, DC-to-AC inverter, which, in turn, supplies 240 VAC, via the circuit breaker, to the existing, step-up transformer for subsequent distribution to the system loads. The 240-VDC bus, located between the rectifier and inverter, is also supplied by two, paralleled 7.5-kW photovoltaic (PV) arrays and two, paralleled 375-Ah battery strings. For the purposes of this document, the PV arrays and the battery strings are considered as part of the inserted, RPS-150 module. In the initial or existing system, the diesel generator output was supplied to the existing, step-up transformer directly, via the indicated breaker.

The second RPS-150 module, shown in Fig. A.1 with its interconnected PV arrays and battery strings, is essentially the same as the first. The two are connected and operated in parallel by synchronizing the operation of the two DC-to-AC inverters. In a similar manner, i.e., via synchronization of the inverters, additional modules could also be added.

The RPS-150 module was designed with a view toward developing a standardized module suitable for insertion into numerous existing diesel-powered RAPS systems. It is modular, its ratings (capacities) are convenient for many existing systems, and it can be incremented to be suitable for many other existing systems by adding additional modules in parallel. Thus, it can become a standard, reliable module suitable for insertion into a many existing diesel-only powered systems.

The hybrid RAPS illustrated in Fig. A.1 has several advantages over the original, diesel-only powered electrical system. The PV arrays, which convert solar insolation to electricity directly, supplement the diesel-generated electricity, thus providing additional electricity to power community loads. The batteries buffer both power and energy requirements such that, to supply a given load, the generator can be operated fewer hours and under more optimal loading. The parallel, hybrid configuration also provides multiple options for controlling battery state-of-charge. Thus, within the constraints of its power and energy ratings, the hybrid configuration can supply continuous, high-quality electricity to a community while improving fuel efficiency, reducing diesel engine maintenance and optimizing battery life and performance.

Several component failures and system anomalies delayed full-scale operation of the Padre Cocha hybrid RAPS. Initially, on-site observations of operating parameters were limited by a lack of diagnostic instrumentation. Subsequently, a power quality meter was made available, which greatly enhanced diagnostic capabilities. The following observations of the system during the start up period were very instructive:

1) Initially, power factors evident through out the system were incredibly low. An obvious contributing factor was that all of the transformers in the system were lightly loaded such that transformer-magnetizing currents were likely a large portion of the total current.

2) There were multiple failures of the input diodes to the chargers. These tended to occur after a brief interim of operation and, thus, were thought to be due to heating. A high harmonic content in the charger input (i.e., generator output) was likely a contributing factor.

3) The hybrid system operated reasonably well with the diesel generator off and the system powered entirely from the two, paralleled d.c. buses. This observation supported the notion that the charger diode failures were associated with the generator output (see 2 above). Subsequently, a three-phase, wye-connected capacitor bank was connected across the wye-connected generator output. It isn't entirely clear what the net result of that addition was (there was little opportunity to make observations before other interventions also became factors), but the capacitor bank would certainly have reduced the harmonic content

of the diesel output. Nevertheless, operating only from the d.c. buses, the distribution system power factors continued to be surprisingly low.

The above observations were suggestive of two, likely independent, problems, i.e., a generator output rich in harmonics and a highly reactive (as opposed to resistive) distribution system. The capacitor bank on the generator output (see 2 and 3 above) was a response to the former. Perhaps as a partial response to the latter, an inspection of the existing distribution system was initiated. Correspondence relevant to this inspection indicates the discovery and correction of some system anomaly(s) [A1, A2], but it isn't clear that these have been documented. With these changes in place, subsequent hybrid RAPS operations have been entirely acceptable. The system power factors have remained somewhat low, but they are much higher than previously and are not unreasonable. It is important to document what was discovered and what was changed about the distribution system that helped resolve the power factor problem, especially if it could be a factor in other hybrid RAPS conversions.

There is also correspondence discussing modifications or perhaps an exchange in charger input or control circuit cards [A3, A4]. This information should also be incorporated in the system documentation, especially if it was a factor in achieving successful operation of the system.

As a further response to the low power factors, Peruvian authorities plan to reduce the number of distribution (step-down) transformers in the system from four to two, both 50 kVA (thus, removing one 100-kVA and one 50-kVA transformer). This will increase loads on the two remaining distribution transformers, which should further increase system power factors.

The Padre Cocha experience also suggests that one should not assume that a significant degree of standardization exists among small utility systems in remote regions and, further, that any existing systems' descriptions, documentation, schematics, etc., should be considered suspect until their validity is reasonably confirmed. (A system may have been modified, for example, and, thus, differ from existing documents.) In lieu of adequate documentation, a reasonably definitive description of the system should be prepared. Before any additional modifications are made, existing system performance parameters should be documented to a reasonable extent. For example, in three-phase systems, line- and phase-voltages and currents should be measured under operating conditions and compared for reasonable balance. Power quality parameters, especially power factors, should be measured and recorded.

Prioritizing among multiple communities as a site for installing an initial hybrid RAPS or upgrading an existing power supply to a hybrid RAPS involves considerations beyond the scope of the issues considered here. The technical issues discussed here assume an existing system with a diesel-powered or otherwise dispatchable generator and a distribution system. Nevertheless, the issues discussed here may also be applicable to other conversion situations.

References

[A1] Correspondence, e-mail from Marcos Alegre to Doug Danley, September 11, 2003.

[A2] Correspondence, e-mail from Marcos Alegre to Jerome Cole, September 22, 2003.

[A3] Correspondence, e-mail from Marcos Alegre to Jerome Cole, October 16, 2003.

[A4] Correspondence, e-mail from Marcos Alegre to Jerome Cole, October 17, 2003.

ANNEX B

Safety Consideration

Voltages encountered in RAPS systems tend to range from several hundred to several thousand volts. Contact with even the lowest of these voltages can be damaging and even lethal to human beings. Thus, it is essential that casual, accidental access to these voltages be prevented and that only qualified, trained personnel have access to these voltages.

In an electric circuit or system, current (amperes) flows between points at different voltages. In general, the Earth is at ground potential (V = 0), and many points on a RAPS system will be 'grounded' or at zero volts. Humans get an electric shock, i.e., current flows through their bodies, when they contact different potentials and, thus, become part of an electric circuit. Under these circumstances, an electric current will flow from the higher voltage, through the human body, to the lower voltage. Depending upon the current-density magnitude, which is inversely proportional to the impedance of the path, this current can be damaging and, perhaps, lethal. Its physiological effect is a function of both its magnitude and frequency. At high frequencies, i.e., above about 1 kHz, the effects of the current are mostly thermal, causing burns and other related problems. At 50 Hz or 60 Hz, i.e., power line frequencies, the physiological effects are about the same as at direct current (d.c.) and will vary among individuals, with the nature of the contact, and with current density within the body. If the two contacts are the hands, for example, the current density will be greatest near the contact points, i.e., the hands, and least at the center of the thorax where body volume is much greater. The body's greatest resistance to current flow is the epidermis or outer skin. For analytical purposes, a point of contact with dry skin is usually considered to be about 1000 ohms. Internally, the body is a good conductor, somewhat equivalent to seawater.

Because 60-Hz current is so prevalent, its effect on the human body is also the best characterized. The effects listed in Table B.1 are average, threshold values, assuming gross anatomical contact with the electric source. The values listed in Table B.1 should apply to d.c., 50 Hz, and 60 Hz equally well.

The distribution voltage at Padre Cocha is nominally 22.9 kV. It is generally unnecessary and always inadvisable to measure electrical parameters at such high levels unless built-in provisions such as current and voltage transformers are present. In any event, parameter measurements should be restricted to personnel familiar with electrical safety principles.

Table B.1 Physical Effects 50-Hz, 60-Hz and d.c. Current on the Human Body

Magnitude of Current in Amperes (A)	Effect on Body
1 mA	Level of perception, 'tingling' sensation
10.5 mA	'Let go' current limit (women)
16 mA	'Let go' current limit (men)
20 mA	Respiratory Paralysis
75 mA	Ventricular Fibrillation
1 A	Sustained myocardial contraction
10 A	Burns, physical injury

Note: These values, mostly from [B.1], vary greatly among individuals and with contact circumstances.

B.1 Starmer, C.F. and Whalen, R.E., "Current Density and Electrically Induced Ventricular Fibrillation", Medical Instrumentation, Vol 7, No. 2, (1973).

ANNEX C

AN ABSTRACT OF THE NEWNHAM AND BALDSING STUDY

Newnham and Baldsing have described, in appreciable detail, a best-practice battery control strategy for the SunGel battery [C1]. Significantly, this practice exploits the gel-VRLA cell's compatibility with PSoC operations. The practice was developed via experimentation with a 24-V battery assembled with cells identical to the SunGel cells in use at Padre Cocha.

Specifically, the referenced study used a RAPS load profile modeled after existing RAPS facilities in Peru. The battery-use profiles tested operated the battery in a PSoC for 28 successive days, followed by an equalization charge that returned the battery to a full SoC. This cycle, including the equalization charge, was defined as a master cycle. The choice of 28 daily cycles between each equalization charge was selected as a compromise to minimize the run-time of the diesel generator under low-load conditions (i.e., during equalization and constant voltage charging) and to avoid sulfation of the battery plates. Three different PSoC windows were investigated, a 58 to 83% PSoC window, a 47 to 72% PSoC window, and a 40 to 65% window. Note that the width of each PSoC window is 25% of battery rated capacity.

By observing the positive and negative plate-group potentials, referenced to a standard electrode, of two pilot cells, Newnham and Baldsing were able to compare the merits of the three PSoC windows. They observed that the positive plate potentials were relatively constant as the daily cycles progressed through a master cycle for all three windows. By contrast, negative plate potential grew more negative, almost from the beginning, for the 58 to 83% window. For the 47 to 72% window, the negative plate potential changed little from cycle to cycle through most of the 28 daily cycles. Late in the master cycle, however, the negative plate potential began to become increasingly negative. The negative plate potentials for the 40 to 65% window remained relatively constant, however, throughout the master cycle.

Newnham and Baldsing also observed end-of-discharge voltages (EoDV) as the master cycles progressed. For the 58 to 83% window, the EoDV voltages decreased gradually as the master cycle progressed. For the 47 to 72% and the 40 to 65% windows, however, the EoDV voltages increased through the first 10 (approximately) cycles and then stabilized. Newnham and Baldsing suggested that these increases could be attributed to an improvement in the charging efficiency at lower PSoC windows.