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Requirements for batteries in remote-area power-supply systems based on technical modelling and field experience

D. Butler

Butler Solar Systems Pty Ltd., PO Box 473, Castlemaine, Vic. 3450, Australia

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Abstract

The development photovoltaic/diesel remote-area power supply (RAPS) systems and their structural emplacement in developing countries are discussed. Key areas of importance are identified as economic returns for RAPS systems and the need for centralized control and collection of data. The value of photovoltaic modules as a power source and techniques for maximizing the energy input to batteries from this source are explained.

Keywords: Remote-area power supplies; Batteries

1. Raps system overview

The development of remote-area power supply (RAPS) systems — defined as electrical power-supply systems for remote and isolated homes and farms, rural business enterprises and isolated villages and towns — has been proceeding at an accelerated rate over the past ten years. The RAPS system has developed from a predominantly diesel-based system, or from a situation where there is no power at all in many developing countries, to one where photovoltaic- (PV) and wind-based renewable energy sources are increasingly being seen as the technology of choice. The PV/diesel hybrid or wind/diesel hybrid is emerging as the industry standard system in several developed countries. In many areas, however, the cost of fuelling and maintenance of diesel engines is too high for these to be used as a primary energy source. A major driver for renewable technologies is that the provision of a reliable supply of unadulterated diesel fuel is difficult and costly in many remote areas of the world. The high delivered cost and the often dubious quality of the fuel places a premium on effective utilization of the resource, and makes the value of energy delivered from renewable sources far higher than if it were fed into a conventional centralized grid.

1.1. Economic and structural development

The key technology impediments to RAPS systems will vary with the degree of economic and structural development of the target country.

In developed countries such as Australia, there have been a number of innovations in diesel/renewable RAPS systems. These include bi-directional sine-wave inverters with simple hardware-driven system controllers that usually control for battery voltage and load conditions. More sophisticated software-controlled systems are available. These have the capacity for remote interrogation and control and can be monitored and diagnozed from a central location. At present, the less sophisticated systems are operated and maintained by the user. This is not a satisfactory state of affairs for the following number of reasons:

(i) Users will have varying skill and interest levels and operation and maintenance proficiency will vary widely from system to system.

(ii) There are definite personal risks associated with untrained user maintenance.

(iii) Experience has shown that untrained or partially-trained users make a significant number of simple operational and maintenance errors.

(iv) There is no guarantee of continuity of trained operational and maintenance staff, as the owner/user may change without notice. The new owner/user may have no incentive, or even the ability, to maintain the system.

(v) Insurance companies and regulators may start to take a serious interest in such systems as the numbers grow and will insist on some operational standards.

(vi) In remote areas, access to the required skills for repair or maintenance may be costly.

In less-developed countries, the same problems will exist but access to the required skills may be even more difficult,

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non-existent, or economically impossible. There have been a number of solutions proposed to this well-recognized problem, i.e. (i) use local, 'low-tech', user-maintained systems; (ii) set up medium-technology systems with training programmes for local support; (iii) use a hybrid local support system that is coordinated with a centralized support system that utilizes remote monitoring and fault diagnosis systems that can draw upon high-quality system support from a centralized location.

Of the three options listed above the local 'low-tech' system is superficially attractive, but such systems are rarely effective and always rely on at least one high-tech import. The medium-technology systems will work most of the time, but with variable results due to differences and variations in the local skill base. Experience in one of the most remote areas of Australia, with systems that use local support backed by a centralized monitoring and fault diagnosis unit, has shown that the availability of RAPS systems and the confidence level in the systems is enhanced to a high degree. The investment in remote monitoring and diagnosis is repaid almost immediately. In practice, there is no long-term possibility of any viable technology-based system surviving without a support infrastructure, so the choice of an appropriate infrastructure is critical.

1.2. Economic returns from RAPS systems in developing countries

The most important factor in the development of any infrastructure is the economic development that it brings to the people and to the nation. If the development is designed to bring a large economic benefit to the region, the necessary technical and commercial infrastructure will follow and will in itself help to create the conditions for economic take-off. RAPS systems that do not have a high economic multiplier will not survive beyond the first few years of operation.

1.3. RAPS system componentry

The single user, isolated homestead-type system that is in widespread use in Australia and other developed countries may not be the best or only model for developing countries. Remote village electrification schemes, mini-grids and even locally supported low-capacity extensions to a centralized grid system are by definition RAPS schemes. They require local energy storage and generation.

1.3.1. Energy storage

At this time, the only fully developed and commercialized electrical storage medium is the lead/acid battery. It is available all over the world and is relatively cheap and reliable. There are, however, some problems with this battery when it is applied to RAPS systems. These problems will be detailed in the research plan for overcoming technical impediments.

1.3.2. Technology transfer

Most of the components that are required for a viable RAPS system are already either manufactured in the user country or the technology can be transferred into suitable existing industries.

1.3.3. Small diesel generators

Small diesel generators are either manufactured in the user country or are available through import. Some service infrastructure may exist.

1.3.4. Wind turbines

In countries that have suitable resources, an opportunity exists for the establishment by licensing of a small, wind-turbine manufacturing capacity. This technology is approaching maturity, and rugged and relatively simple designs are available.

1.3.5. Inverters and electronic controllers

Although these appear to be the most complex and difficult components of a RAPS system, they can be manufactured in any country that has the capacity to build consumer electronics. The reliability of these units has improved markedly over the past ten years to a point where units of reputable manufacture are the most reliable part of the system.

1.3.6. Photovoltaic modules

These are rapidly becoming a commodity item, and there is ample evidence that the price will continue to fall at a rapid rate. The cost per unit of electricity generated over the lifetime of the PV module is already competitive with fossil-fuel generation technology in many areas of the world.

1.3.7. Batteries

Lead/acid batteries are already manufactured in many countries and the manufacturing technology is well understood. Nevertheless, the application of lead/acid batteries to RAPS systems is not well understood in user countries or by the industry as a whole. Significant research and development effort is required to remedy the lack of application knowledge.

Nickel–cadmium batteries are currently used in telecommunications and other mission-critical applications throughout the world. The high toxicity of cadmium is a problem, however, and necessitates professional recycling programmes for spent batteries. Spent lead/acid batteries are also classified as toxic waste and suitable recycling programmes will need to be implemented in the targeted market areas. Safe transport of batteries is a major difficulty. Affordable packing and transport systems for RAPS batteries need to be developed.

2. Emerging energy storage technologies and impediments to the large-scale application of lead/acid batteries

A number of emerging electrical energy-storage technologies are approaching commercialization/demonstration. These include zinc–bromine and nickel–metal hydride batteries. On the other hand, given that manufacturing plants for lead/acid batteries already exist throughout the region, it is clear that lead/acid will be the technology of first choice for many years to come.

2.1. Emerging complementary energy-storage and generation technologies

High-temperature, solid oxide fuel cells will be commercialized within the next ten years. These hold out the hope of a low-maintenance, high-efficiency, primary energy source for RAPS systems. They do require a reasonably high-quality hydrocarbon fuel, are a relatively high-impedance energy source, and will not function in a real load situation without a low impedance power source, such as a lead/acid battery, in parallel.

Another new development at an advanced stage of commercialization is the so-called 'super capacitor'. This device promises short-term energy storage that is thousands of times greater than standard capacitors. The application for this capacitor is to be in shunt with the battery energy source so that the battery does not see very short-term power spikes. The capacitors may be beneficial in the reduction of ripple on the battery.

2.2. The importance of photovoltaic cells as an energy source for RAPS systems

Photovoltaic energy sources are an almost ideal energy source for renewable energy systems. They have no moving parts, are entirely solid-state, require essentially no maintenance, and come with 'manufacturers' guarantees of up to twenty years.

The major drawback of PV modules has been the capital cost and the cost of electrical energy storage. PV modules require more storage capacity than wind-power systems because the effective 'on' time of the devices is limited to 5 to 8 h, at best. Wind turbines may produce significant energy for days on end.

2.3. State-of-the-art hybrid diesel-based RAPS systems

These are fuelled, maintained, serviced and monitored by the user or the supplier, which may be the local power utility. They contain sophisticated software-driven controllers, inbuilt data loggers and a communications capability that includes remote parametrization, data downloading, and the ability to communicate with other components of the system including batteries.

2.4. End-of-grid RAPS systems and RAPS mini-grids

In many parts of the world, the most appropriate way to bring energy services to developing areas may be by the implementation of central, grid-connected, low-cost, distribution systems with local energy storage and local power conversion. These systems may also have a capacity for local generation, either from wind or PV. The major economic benefits of this class of system are the potentially low capital cost of the central grid-connection and the possibility of a 'loss free' connection to the central grid. If an appropriate local resource (such as small hydro) is available, such a connection could be a next exporter of energy into the central grid.

3. Technical impediments to RAPS systems in the developing world

3.1. Batteries

Among the components of a modern RAPS system, the lead/acid battery is one of the most difficult to manage. Monitoring of RAPS systems by the author's company has revealed serious imbalances of acid sp. gr. in the cells of high-voltage (> 24 V) RAPS batteries that are required to cycle on a regular basis. The cause of this phenomenon has been attributed to the inability of both diesel- and solar-based RAPS systems to maintain float or boost charge regimes beyond a few hours every day. The duty on the batteries is daily cyclic with short recharge times. There are few, if any, other battery systems that require this mode of operation. High-voltage UPS batteries, for example, do not cycle on a daily basis and power is always available to equalize the cell voltages. Both Gates and Johnston Controls refer in their product literature to the difficulty of equalization for cyclic duty in batteries of more than 24 cells in series.

Extensive field trials by the author's company established that > 48 V lead/acid RAPS batteries of any construction can lose cell equalization after as few as 200 cycles in typical diesel/PV hybrid RAPS systems. Recovery from this situation requires extended equalization at low rates of charge and this is difficult with diesel systems that require high engine-loading to obtain reasonable fuel efficiency and reliable, long-life operation. To achieve equalization, the diesel must run for extended periods at low loads. The hysteresis-type PV controllers in common use in the industry exacerbate the situation. These controllers must be of the constant-voltage type, but only a few of these are commercially available.

Even < 24 V batteries that have been subjected to charge/discharge cycles over long periods exhibit significant drift in cell state-of-charge (SOC), and require extended equalization every few weeks to ensure a reasonable battery life. Again, this low rate of charge and low diesel-load regime is costly, in terms of both fuel consumption and diesel wear.

A major research effort is required to characterize fully the cell-imbalance problem, and to develop charging systems that allow the battery to be equalized under all conditions of operation.

3.2. System monitoring

A few manufacturers produce inverters with built-in system logging and monitoring. These features are essential for the successful integration of RAPS systems into the developing world. The imminent launch of global communications satellites will make possible the centralized monitoring and support that is essential for complex distributed-power systems. An industry standard communications and data-retrieval protocol is required so that the industry can proceed with standard systems and facilitate the centralized monitoring of RAPS systems.

3.3. Centralised data collection, remote fault diagnosis, remote problem fixing

Experience in Australia with RAPS systems in remote areas has shown the value of remote data-collection and diagnostics. Most problems encountered on site have been fixed either over the telephone by the centrally located engineer, or by the local on-site person acting under the direct telephoned instruction of the engineer.

3.4. Poor energy efficiency from some RAPS inverters

The importance of low-load efficiency and low-standing losses in RAPS systems is not fully understood by specifiers or users. Significant work is required to characterize fully the problem of high-standing losses in inverters and other controllers, and to develop techniques for minimizing the effect.

4. Simulations of RAPS systems

To investigate the benefits of PV in RAPS systems, a detailed technical computer model of a sophisticated RAPS system has been constructed. This model uses the same control algorithms that are used in the Butler Solar range of generator-interactive inverters. The results would be applicable to similar systems, but the control algorithms for the generator may be more sophisticated than those in other commercially available systems. The controller is embedded in the inverter and makes decisions on generator start/stop according to:

(i) real battery SOC; this value is computed from a rate-compensated ampere-hour balance;

(ii) time of day; the system is often biased to run the generator between the hours of 6.00 pm and midnight;

(iii) load history; the inverter calculates the load energy and uses the magnitude and rate-of-change of load to determine whether it is necessary to start the generator, and

(iv) renewables input; the inverter calculates the energy from a renewable-energy source, such as PV or wind, and makes decisions based on the magnitude of this input compared with the load energy, the state of the generator, and the battery SOC.

A number of other inputs and internal states are also factored in, and the overall control algorithm is both complex and comprehensive.

4.1. The computer model

The model can run under both Macintosh and Windows environments; files are directly interchangeable between the two platforms. The model appears to the user as a graphical representation of selected system inputs and outputs. Slider bars are provided for input, and graphs and digital displays for output.

The simulation allows the user to enter and define various system entities, such as: inverters, generators, PV arrays, batteries, wind or water turbines, and load, temperature and wind profiles. These profiles are usually 5 day, 15 min averages. The software supports mixed averaging times. The user can enter a new profile from a spreadsheet (such as Excel), or can directly enter data by drawing a graph with a mouse. The solar insolation is described mathematically, and the user can define insolation levels and sun hours. For most work, the model has a simple winter/summer switch that changes the profile accordingly.

Each of the entities is contained in an accurate sub-model, and each sub-model can be changed internally. Over 100 internal system variables and system inputs/outputs can be displayed in both graphic and numeric formats.

The model is run from a control panel that contains the graph tables, the numeric outputs, and the slider bars. The simulation calculates the power and energy flows in the system, as well as the battery SOC. It contains the control algorithms that are embedded in the inverter and calculates important constraints, such as heatsink temperature, by using inverter power and a model of the inverter as input.

4.2. Units

The model uses power and energy as the fundamental modelled variables in units of kWh. Battery SOC is modelled. Temperatures, i.e. those at ambient, heatsink, PV array and battery, are given in °C. Amperes, volts and volt-amperes reactive are not used explicitly, but can be derived and displayed if required. Most models assume power factor loads of unity, but the power factor can be altered if desired.

The benefit of using fundamental units, such as power and energy, is that they are easily scalable and the setup time of the model is kept short. The battery SOC is a normalized value, i.e. 100% SOC = 1.

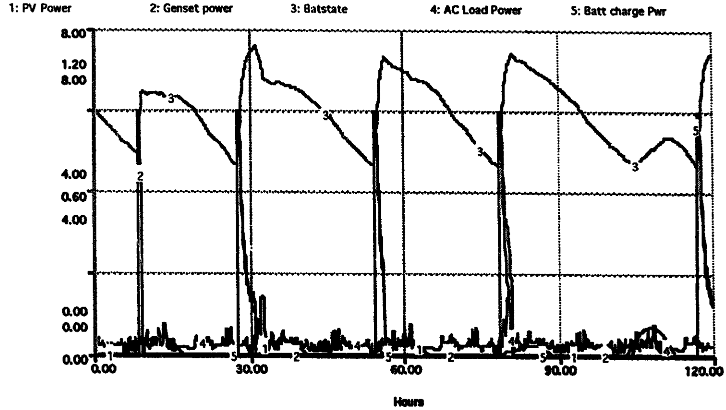

Fig. 1. Simulation of a 6.4 kWh/day RAPS system.

4.3. *Simulation results*

Fig. 1 shows the output from a simulation of a RAPS system that was configured with: (i) a 5 kW, fully reversible, sine-wave inverter; (ii) a charge rating of 5 kW; (iii) a generator of 6 kW; (iv) 1 kW of PV modules; (v) a battery size of 13.6 kWh; (vi) an a.c. load of 6.4 kWh; (vii) a d.c. load of 0 kWh, and (viii) a winter insolation profile.

The simulation shows considerable cycling of the battery and gives a generator run-time of about 12 h over the five days of the simulation. The PV utilization is given as 56.6%, and the generator utilization as 59%. Clearly, the PV utilization is poor and, in fact, if the system energy curves are examined, it can be seen that the PV is doing little but make up the battery and system losses. The reason for the poor PV utilization is that the battery SOC is high due to frequent generator starts and the small size of the battery.

The energy relationships in a 6.4 kWh/day system are shown in Fig. 2. It can be seen that there is a poor match between prospective PV energy (trace 4) and delivered PV energy (trace 2). The simulation accounts for all the losses in the system and contains either expressions or internal graphical representations of system elements. The battery charge acceptance and losses are modelled by internal graphical representations, as they are complex and easier to represent graphically. The simulation software is modular and easily modified for special purposes. There is a wide choice of outputs and an Excel-compatible spreadsheet may be output. The ability of the software to deliver an expanded view of the simulation is demonstrated by Fig. 3. Any time period can be selected for display. The vertical axes can be re-scaled as well.

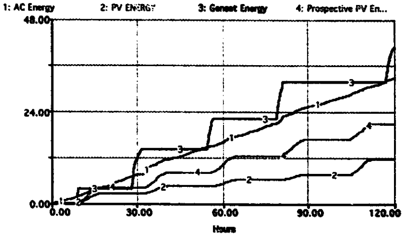

Fig. 2. Energy relationships in a 6.4 kWh/day RAPS system.

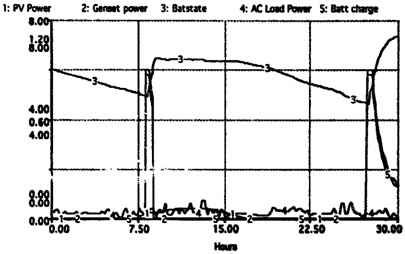

Fig. 3. Expanded view of simulation of a 6.4 kWh/day RAPS system.

The effect, during five days in winter, of doubling the battery size to 27 kWh in the 6.4 kWh/day system is shown in Fig. 4. The generator hours have been significantly reduced to 8.9 h over the five days and the PV utilization is lifted to 74.3%. The downside is that the generator utilization has dropped to 52.4%. The increased cost of the battery will have

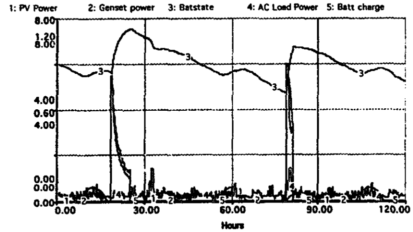

Fig. 4. Effect of doubling battery size (to 27 kWh) in the 6.4 kWh/day RAPS system.

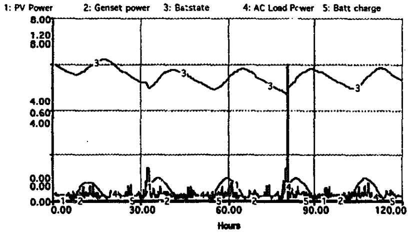

Fig. 5. Simulation of 6.4 kWh/day RAPS system: response to summer insolation.

to be factored against the reduced run-time of the diesel genset. The simulation demonstrates the need for adequate battery sizing to enable the full utilization of the PV energy input.

One of the major benefits of this simulation program is that it enables the rapid near optimization of system components, and reduces the need for extensive field trials. Careful designers will use field trials to confirm the results, and then feed the results of the field trials back into the simulations.

The system response to summer insolation is shown in Fig. 5. The prospective PV energy is now 38.2 kWh over five days, and the PV utilization factor is 91.1%. The diesel run-time is only 20 min for the five days, and the generator utilization is 100%. This system could be said to be summer optimal.

The effect of doubling the battery size and the input of summer insolation has been a dramatic increase in the utilization of both the PV resource and the generator. The energy curves given in Fig. 6 show that the average energy from the PV is greater than the average load energy. The generator start is due to the co-incidence of a load peak and a transiently low battery SOC. The inverter software is able to recognize the increasing PV input, and shuts down the generator in response to this.

The benefit obtained from the addition of another 500 W of PV is demonstrated in Fig. 7. The average battery SOC is good and the generator does not start; the battery discharge

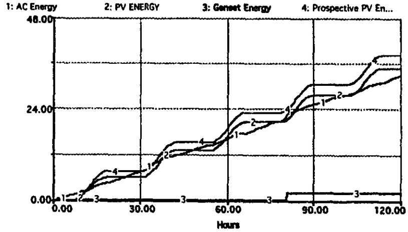

Fig. 6. Energy curves for 6.4 kWh/day RAPS system.

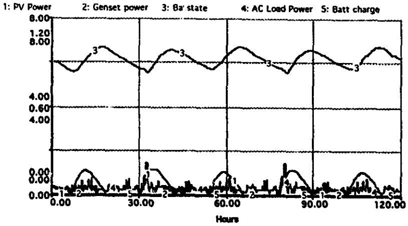

Fig. 7. Simulation of 6.4 kWh/day system: benefit of adding a further 500 W of PV.

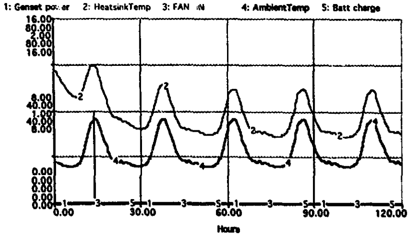

Fig. 8. Simulation of 6.4 kWh/day RAPS systems: inverter heatsink temperature.

is small and the battery is expected to enjoy a long life. Note also, the battery SOC is regularly 100%.

The temperature of the inverter heatsink during the above period of simulation is plotted in Fig. 8. The initial heatsink temperature was chosen as 40 °C above ambient. This has caused the cooling fan to come on during the first day. Note that there is a downwards trend of the heatsink temperature for all five days. This indicates that the inverter is well able to cope with the loads.

The system response to a three-times increase in load over five days is presented in Fig. 9. Clearly, the system is robust and able to cope with periods of overload and an ambient temperature of 38 °C. The fans are controlling the heatsink at the desired set point (60 °C). Note that the strategy of a software bias towards a 6.00 pm start moves the battery

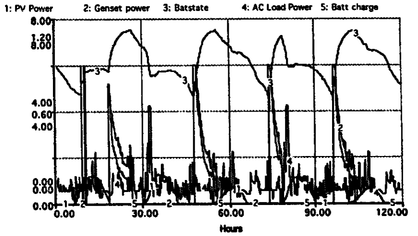

Fig. 9. Simulation of 6.4 kWh/day RAPS system: system response to three-times increase in load.

recharge into the cooler evening period and lessens the thermal stress on the inverter. The inverters used in these systems are able to run continuously at full load at 45 °C. Excursions of 50 °C are permitted for durations of up to 1 h. The inverter software will de-rate the inverter in charging mode if the heatsink temperature rises above 80 °C, or start the genset if heavy loads cause elevated heatsink temperatures. The inverter is actively self-synchronizing and paralleling and, thus, is able to unload itself in the event of severe system overload.

4.4. Simulation summary

The above simulations that use real load data, and that have been shown to correlate closely with real world systems, illustrate some of the complexity and difficulties associated with RAPS systems that have to deal with diversified loads and intermittent renewable inputs. The experience with this simulation system has demonstrated that the simple rules-of-thumb used by systems' designers are far too crude to yield least-cost systems. It is essential that the systems be modelled comprehensively and in fine detail if proper results are to be achieved.

5. Conclusions

The RAPS industry does not have adequate tools to design what are very complex systems. The elements of such systems may seem simple — batteries, inverters, generators, controllers and renewable inputs — but the interaction of the elements is very complex and their correct sizing is a demanding task. The development of software to control adequately RAPS systems is an ongoing task, and the ability to model accurately the systems enables software designers and system designers to test quickly the effect of software changes.