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A PHOTOVOLTAIC GENERATOR ON COCONUT ISLAND

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Summary

A description is given of the design principles of a photovoltaic–diesel power generator that has been constructed on Coconut Island, Torres Strait, to supply a village of 130 people with 240 V: 50 Hz electricity. Even though the solar fraction is only 0.4, the system sets a precedent for Australia with an array size of 23 kW. The uniqueness arises, however, from the fact that it is a stand-alone, inverter-driven system of considerable size with a sine-wave output.

Introduction

Although Queensland has abundant resources of coal, and the bulk of the State's electricity is supplied by coal-fired thermal power stations, there are some areas where it would be uneconomic to supply electricity from the grid. For these areas, a study has shown that photovoltaic (PV) energy could be attractive. As a result, a PV–diesel power station has been constructed on behalf of the Department of Community Services and Ethnic Affairs, Queensland, for a remote community of 130 people living on Coconut Island, Torres Strait.

Choice of electricity-supply system

A primary objective was that the islanders should receive the same quality of electricity supply as that enjoyed by mainland consumers connected to the grid. The expectation of the islanders was that they would be able to operate the same range of appliances, with the same level of convenience, as urban dwellers. It was thought that this expectation might be met by systems other than the conventional 240 V: 50 Hz a.c. system, since some of the options could be more compatible with PV generation and/or available components. Particular attention was given to 110 V d.c. and 240 V square-wave systems.

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Direct current distribution was an obvious consideration since the electricity derived from a PV-battery system would be generated and stored as d.c. Certainly, a.c. would be required for some appliances but others could operate perfectly well on d.c. One option would be to distribute the electricity as d.c., to utilize as much as possible in that form, and to invert to a.c. only for those appliances that could not operate on d.c. The attractions of such a strategy would be a considerable reduction in inversion loss and a reduced reliance on a critical system component, namely, the inverter. In the final analysis, the limited range of d.c. appliances, the possible need for a d.c./d.c. converter to produce a constant d.c. potential, and the distribution losses at 110 V, all reacted against the system.

Square-wave inverters have been used for many remote-area systems on the grounds that the units are both simple and efficient. It is claimed that most appliances work satisfactorily with the square-wave output, though electric motors are less efficient and subject to greater thermal stress. Manufacturers had little experience with inverters above 1 kW and practically no experience of parallel operation. Also, the standard of protection applied to the smaller inverters seemed inadequate. On the other hand, there were difficulties with sine-wave inverters. Thus, although it was agreed that a sine wave was preferable, a square-wave system would not be excluded on the grounds of its waveform alone.

Resulting from the consideration of the supply, a desirable specification was developed as follows:

Potential:	240 V ± 6%
Frequency:	50 Hz ± 2%
Harmonics:	not greater than 3% total harmonic distortion
Continuous service:	outages should not exceed 9 h per year
Appliances:	heating appliances and air conditioners are not permitted
Metering :	energy metering for each consumer.

It was felt that the decision to disallow certain appliances and to meter energy was the best approach to containing the system capacity.

Development of a performance specification

To meet the requirement of continuous service, a PV–diesel facility was nominated, and a performance specification written for a system to meet a design load (Fig. 1) at a design solar fraction of 0.4. The design load was based on the estimated use of the 30 residences, store, assembly hall, school, kindergarten, etc., and included a daily allowance of 6.5 kW h per occupied residence. The system should be designed to produce about 75 000 kW h per year at a peak output of 15 kW. (It should be noted that the solar fraction was reduced from a desirable level of 0.85 to meet budget requirements. The reduction in solar fraction was believed to be a better means of achieving the objective of evaluating the system, rather than reducing the

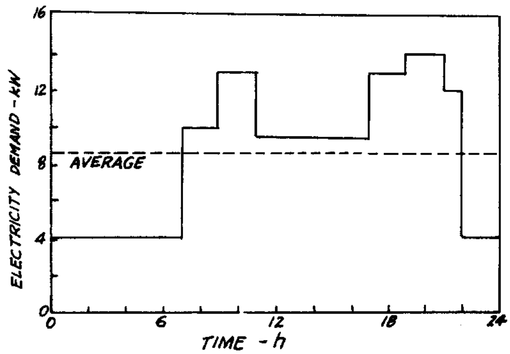

Fig. 1. Design load for community on Coconut Island.

overall system size, since the characteristics of the original system were preserved.)

In order that the solar fraction could be calculated in the absence of weather records, the monthly average-daily-insolation was estimated from several correlations [1], and the monthly average temperature was inferred from data for the nearest recording station, Thursday Island. A specific method of calculating the solar fraction was nominated to ensure that all options were evaluated in the same manner [2].

Achieving reliable operation was a major consideration that was approached with four initiatives: modular construction; component back-up; failure protection; quality assurance. Modular construction with components of the same type in parallel avoids total system shut-down in the event of failure of a single component. The solar array and the battery bank are normally modular, with the unit components (PV modules, battery cells) being arranged in a series string to yield the required electrical potential for the system. Several such strings are joined together in parallel to give the desired system capacity. Failure of a component in a string may deactivate that string but should not affect the remainder, so that the system can continue to operate. The concept of parallel operation was extended in the Coconut Island facility to diesels, controllers, and inverters. Spares are carried to enable replacement of damaged modules, and to allow the system to return quickly to normal operation.

An example of component back-up is the use of the diesel alternator to supply the output directly in the event of inverter or battery failure. This option is a sufficient reason for the use of an alternator with rectifier for battery charging rather than the employment of a d.c. generator.

Sensing the malfunction of a component and raising an alarm may protect the system against shut-down or complete failure. Examples of these alarms could be diesel failure to start, diesel control supply failure, and diesel shut-down.

A quality-assurance programme was proposed in the specification. In general, it was based on Canadian Standards [3] and had four sections:

examination of type test certificates of components; design approval; testing of critical components; inspection, including testing, of the installation.

Closely allied to reliability is safety of personnel and equipment. Design aspects considered included electrical safety, lightning and fire protection, structural strength against wind forces, etc. It was mainly from the viewpoint of safety that underground electrical distribution was selected. The following specific design approaches were examined but not made mandatory.

Maximum power point tracking. To match the maximum array output to the battery charge requirements effectively may require a d.c./d.c. converter. The cost/benefit of possible devices could not be evaluated easily since no proven commercial units with sufficient current-carrying capacity were available. Further, the effect of such a device on system reliability was another unknown.

Load management. Since cost-effective, stand-alone generators will not have significant spare capacity, it can be expected that they will regularly run close to full load. Since the maximum possible connected load will exceed the full load, an overload will sometimes occur. Under these conditions, it is preferable to switch off low-priority units rather than to shut down the entire system. Although audio-frequency controlled switching of such units is possible, it was considered expedient to give an audible warning of overload so that the operator would reduce the load manually. An overload situation could also occur on a "black" start (*i.e.*, when the generator was turned on after a period off line), through the combined starting current of refrigerators and freezers should it be attempted to start all the units simultaneously. In practice, however, there is some delay built into most refrigerators so that simultaneous starts do not occur.

Supervisory control. Where control elements and alarm sensors are distributed among many components, a supervisory control system can improve system management and increase reliability. It was thought that a programmable controller would be effective for the system.

Cross-connection of solar cells. Hot spots can arise in series- and parallel-connected arrays when high-resistance cells are created by shading or breakdown. The effect of cross-connection on this phenomenon has been studied [4] and one approach, bridge connection, has been recommended as a means of reducing the risk of damage. Nevertheless, this approach was not evaluated in detail as it appeared impractical for the array selected for Coconut Island.

System design

Components

Circuit design has been the responsibility of the contractor who had to produce a system of the required performance to meet the load. The basic system consists of four components — PV array, battery, diesel generator, inverter — connected by a distribution line to the load (Fig. 2). Each of these components has been sized and provided with a control circuit. In addition, the modular approach has been addressed.

The following is a brief description of the system as constructed on Coconut Island:

d.c:	110 V nominal; 105 - 135 V operating.
a.c.:	240 V; 50 Hz; single phase; 15 kV A.
PV module:	Arco, 12 V; 53 W; efficiency = 12.4%.
PV array:	468 modules; 52 strings of 9 modules; 24.8 kW at 1000 W m^{-2} insolation.
Battery:	BP Solar, Type 2P1101 cells; 1101 A h at *C*/100 rate for each cell; 220 cells; 4 strings of 55 cells; 4404 A h for battery.
Diesel:	Lister HL4; 37.5 kW; 2 units.
Alternator:	29 kW; 3 phase; 2 units.
Rectifier:	160 A; 2 units.
Inverter:	Nova; sine wave; 5 kW; 3 units.
Controller:	IPC Programmable.

The array is divided into four sub-arrays, each with its own charge regulator that can act independently. Likewise, there are four strings to the battery. Two separate diesel–alternator–rectifier sets are provided. Normally, these sets will operate together to charge the battery. One of the alternators has external connections so that it can produce single phase and be switched to the load manually in an emergency. Three inverters operate in parallel (Fig. 3). An option to cascade the inverters (*i.e.*, to bring inverter modules on to meet the load) was not included due to design difficulties.

Determination of component size

Since the demand for power was largely unknown, a system load curve was estimated from the capacity of the expected appliances, some observa-

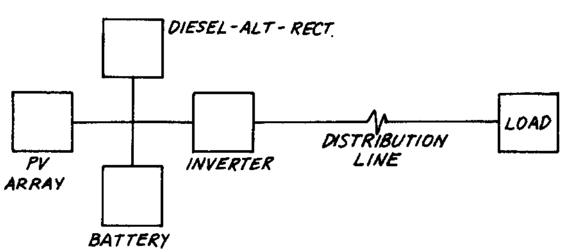

Fig. 2. Basic components of power generator.

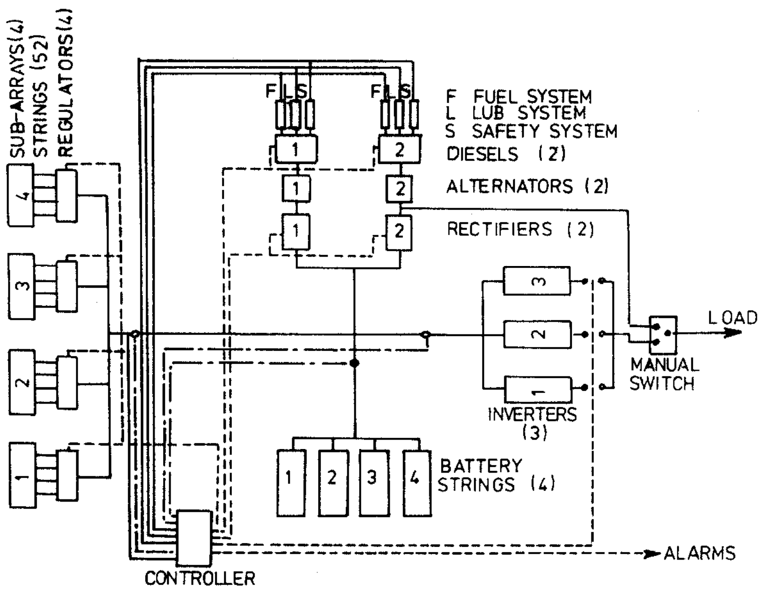

Fig. 3. Schematic circuit of power generator.

tions of the islanders' habits, and some assumed diversity factors (Fig. 1). It can be seen that the base, peak, and average loads are 4.1 kW, 14 kW and 8.6 kW, respectively. The inverters must supply the peak load together with an allowance for line losses. Thus, three inverters, each of 5 kW, were chosen. (Note, the inverters eventually supplied were 5 kVA and produce only 4.5 kW at the normal power factor of 0.9.)

A preliminary calculation for the total number of PV modules can be made from the annual average daily insolation and the load. The number selected must be divisible by 36 (9 modules are required in a string to reach the charging voltage and there are 4 equal sub-arrays). It was calculated that 468 modules would give a solar fraction of 0.427, which was satisfactory. A more detailed calculation of the solar fraction was made from the monthly average-daily-insolation, using a method based on f-charts [2]. The value found was 0.44 which confirmed that the design met the specified level of 0.4.

Since the battery size has only a small effect on the solar fraction, and will be uneconomically large if required to store sufficient energy to cope with the known sequence of cloudy days, the size was based on a criterion that allowed one diesel start every two days. Under average weather conditions, the number of hours that the load is supplied by the diesel, the solar array or the battery can be estimated. The battery ampere hour contribution can, in turn, be determined, and must be supplied as the battery discharges over its operating range to 40% state-of-charge (SOC). The required ampere hour capacity can be found at the average discharge current and converted using Peukert's equation to the nominal $C/100$ rate. It was

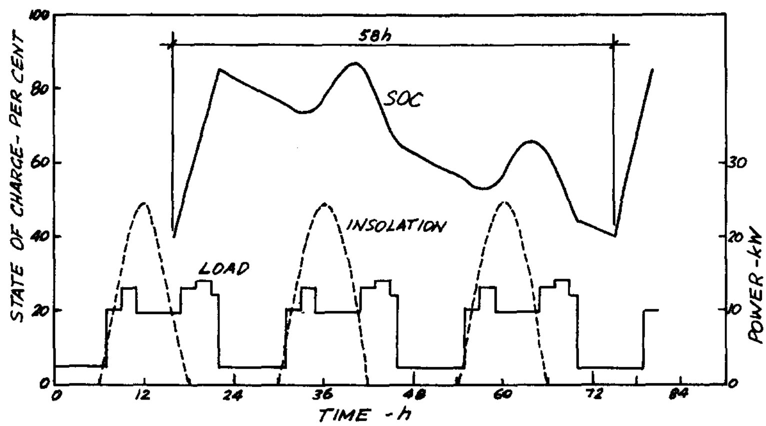

Fig. 4. Hourly calculation of battery state-of-charge (SOC).

found that around 3400 A h were required; the available capacity from the chosen battery bank was 3525 A h at the average discharge current or 4404 A h at the $C/100$ rate.

The battery SOC during operation was predicted on an hour-by-hour basis. For the case of clear skies, calculation (Fig. 4) showed that the interval between diesel starts was 58 h. For cloudy days, the period would be less. Several hourly calculations with different amounts of insolation confirm that the chosen size of battery should be suitable to limit diesel starts to around once in 48 h.

After determining the battery parameters, the diesel charger (consisting of a diesel–alternator with rectifier) was chosen to recharge the battery in conjunction with the PV array at the maximum recommended rate of 0.167 $C/10$. The battery capacity at the $C/10$ rate is 2640 A h. Actually, it was thought that two chargers would improve reliability so 160 A units have been selected to give a charging rate (without PV input) of 0.121 $C/10$. To drive the chargers, 37.5 kW diesels with 29 kW three-phase alternators are used. At full charge, the diesels are on about 90% load, a value considered as satisfactory. Air cooling of the diesels was selected for added reliability.

Control

Control is effected by a microprocessor-based system controller that handles one sub-array, diesel generators, protection, and alarms. Separate charge regulators control the other sub-arrays. In addition, devices within the inverters control the a.c. output, while time-delay switches prevent overload during system start-up.

There are five normal modes of system operation, namely:

- solar charging
- diesel charging
- solar charge regulation
- load management
- normal discharge

The array will output current when there is sufficient sunshine for its voltage to exceed the battery voltage. At low levels of insolation, the array output will supply the inverter. However, once the array output exceeds the inverter input requirements, the excess will go to charge the battery.

Solar charge regulation occurs when the battery is near full charge and the load demand is less than the available solar-derived energy. At this point the controller puts the array into a low-frequency pulse-charging mode, allowing the battery to accept current up to full charge without excessive gassing. Pulsing is effected by open-circuiting the array when the battery voltage reaches a pre-determined set point of 2.49 V/cell at 40 °C. (Note, all subsequent voltage settings given in this paper refer to an operating temperature of 40 °C.) Without the charging current, the battery voltage falls to the normal discharge voltage. When the battery voltage reaches 2.30 V/cell, the array is reconnected, causing the voltage to rise to the disconnect set point again. The frequency and duration of the pulses are a function of the charging and load currents and the battery SOC. Once the battery has accepted sufficient charge to keep the discharge voltage above 2.30 V/cell for extended periods the battery is considered to be fully charged and the array remains open-circuited. The sub-array controllers are regulated at slightly different set points to allow staged connects and disconnects and so reduce power transients. Normal discharge occurs when there is no charging current from either the PV array or diesel generators.

Diesel charging is activated when the battery reaches 40% SOC, as indicated by a battery voltage of ~1.87 V/cell. The controller provides a software delay in starting the engines in order to prevent nuisance starts. The controller also provides three-shot cyclic cranking, with each cycle consisting of a 15 s crank and a 15 s delay. If the engine has not started after three attempts, the engine is shut down and a generator failure alarm is sounded. The two engines act independently for starting so that if one fails to start, the second one is not affected. Diesel charging continues until the batteries have reached 95% SOC (~2.47 V/cell). At this point the controller stops the engines. Once every twelve cycles (*i.e.*, about every four weeks), the controller will leave the engines on for an equalising charge of 3 h. Besides equalising the charge between cells, the accompanying gassing mixes the electrolyte and helps prolong battery life. The controller also provides weekly diesel exercising if the engine has not started because of low loads.

The load-management function is a two-stage, low-voltage, battery protection scheme. The first stage is a low-voltage alarm activated when the battery voltage falls to 1.80 V/cell. Should the voltage continue to fall to 1.78 V/cell, the controller disconnects the inverters entirely. The latter would be automatically reset when the voltage rose to 1.98 V/cell. The low-voltage load-disconnect function operates under a fixed hardware delay of 90 s. The system voltage must remain below the disconnect threshold continuously for this time in order to disconnect the loads. Load disconnect is an emergency function designed to protect the batteries from irreversible damage caused by excessive discharge.

The inverter must control the output voltage to within ±3% as the output current changes from no load to full load and the input voltage varies from −10% to +20% of the nominal. The frequency must be maintained within ±1%; this precision is easily achieved with crystal timers. Protection is provided by shutting down the system if: (i) input voltage is outside the above limits; (ii) the output voltage is outside ±5% of nominal; (iii) critical components become overheated (over-temperature) thus indicating overload or failure.

Alarms are an essential feature of any unattended plant. In the case of the Coconut Island facility, alarms have been installed to respond to the following events:

Diesel	— Failure to start
	Low oil pressure
	High engine temperature
	Control supply failure
	Unscheduled shut down
	Low fuel level
Rectifier	— Fire
	Fuse open-circuit
	Low voltage
	High voltage
Inverter	— Over-temperature
	d.c. low voltage
	d.c. high voltage
Shelter	— Fire (3 detectors)

Site layout

The solar power station has been erected some 200 m to the east of the village and supplies power through an underground cable to more than 30 consumers. Several consumers are connected to each ground-mounted cable-box (Fig. 5).

For convenience and to avoid cutting down trees, the arrays and power station building have been located adjacent to the inground storage tank of the island's recently installed water system. The remoteness from the village has removed any need for a curfew on diesel operation due to noise. The arrays have been aligned with the edge of the water tank; the horizontal projection of the surface normal points some 5° - 6° East of North. With this orientation, it has been calculated that the effective reduction in radiant energy received on the surface is less than 1%.

A shelter to house the batteries, diesel generators, and control equipment is mounted to the south of the arrays (Fig. 6).

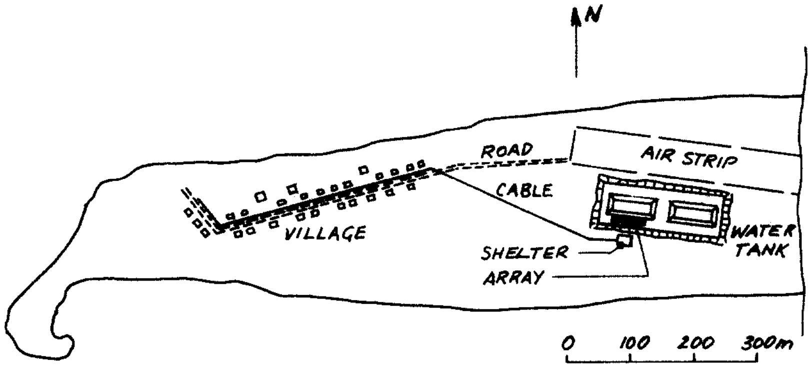

Fig. 5. Generator site on Coconut Island.

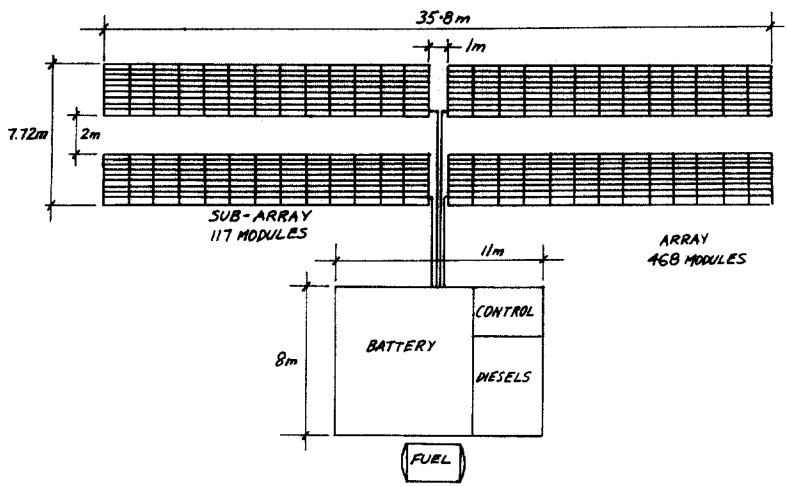

Fig. 6. Layout of photovoltaic arrays and equipment shelter.

Construction

Much of the site preparation, laying of foundations, erection of the pre-fabricated battery shelter, and assembly of arrays, was sub-contracted to the Island Council and supervised by the main contractor. Sand and aggregate were shipped to the island because the client was not prepared to risk using "island sand" (broken coral and shell material) due to its chlorine content. Fortunately, the newly installed catchment and tank provided adequate water.

A quality assurance programme was developed on the basis that all components were commercially available. Elements of the programme were:

- inspection of type test certificates;
- approval of system design;

- testing and approval of critical components;
- inspection and acceptance.

There was great difficulty in achieving the programme as envisaged, for the following reasons.

(i) Test certificates for components were either unavailable or inadequate. While it would have been preferable to have certificates from independent authorities, it was agreed that in-house test data would be acceptable. Even this was not available for all components. A particular case was the battery for which relevant "representative" charging data were not readily available. Since these data could not be guaranteed and the control system set-points were dependent on the battery performance, the final settings could not be determined until the battery was tested in the author's laboratories as a "critical" component.

(ii) The design was not completed in the stipulated time, with the result that approvals had to be given on sections of the system before the design could be evaluated as a whole.

(iii) While some components were delivered in reasonable time, the inverter was so delayed that arrangements had to be made for testing at the manufacturer's works.

Despite these problems and compromises, an excellent design has been produced which meets all the requirements of the specification.

System monitoring

So that the system can be supervised from the headquarters of the Department of Community Services and Ethnic Affairs in Brisbane, and so that a detailed analysis can be conducted of the performance of the innovative power unit, data are being collected and transmitted via satellite. The equipment consists of a data logger, micro-wave transmitter, satellite, receiver, main-frame computer, land line, and personal computer (PC).

Data are first collected and stored by the logger. Initiated by a signal from Brisbane, the data are then transmitted at regular intervals (or on demand) for storage in the PC. Later, the PC is used to analyse the information and to present results in tabular or graphical format. Full details of this system are to be published at a later date.

Operation

The plant has been operating since late 1987, and has performed to expectations. While some component failures have been experienced, the parallel paths and the stand-by feature of the diesel have resulted in the plant being off-line for only a brief period.

The performance can be gauged from the diurnal values of the main variables. Power demand (Fig. 7) shows an unusual pattern with relatively

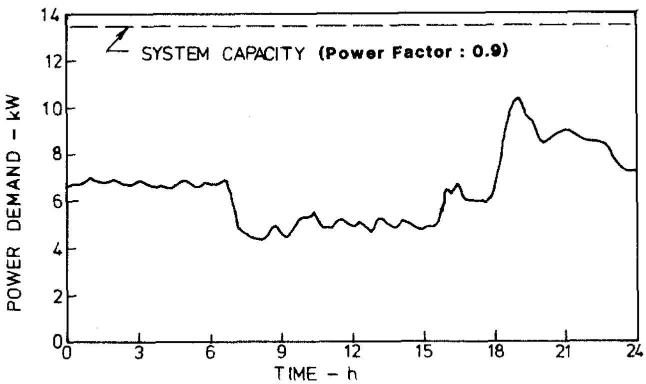

Fig. 7. Diurnal power demand on Coconut Island.

high consumption at night due to street and house lighting. The peak demand of around 10 kW is typical, though currently this value is approaching plant capacity as more domestic appliances are being installed.

The a.c. voltage (Fig. 8) is steady and well-within the desired limits, while the d.c. voltage increases steadily from about 06.45 h, indicating that the battery is being charged. When the system's d.c. currents are examined on days when the diesel starts (Fig. 9), the source of the charge is seen to be both the diesel and the array. Furthermore, the inverter current has a similar pattern to the demand (refer, Fig. 7). From midnight to about 06.45 h, the battery current is negative, indicating that the battery is supplying the inverter. Then, the diesel starts as indicated by the rectifier current, changing the battery current to positive, *i.e.*, a charging regime. At about 06.45 h, the array commences output, which further increases the charging current.

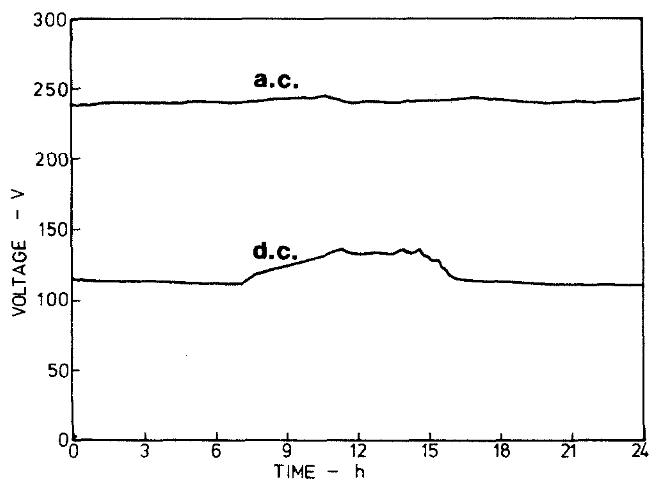

Fig. 8. Diurnal a.c. and d.c. voltage of power generator on Coconut Island.

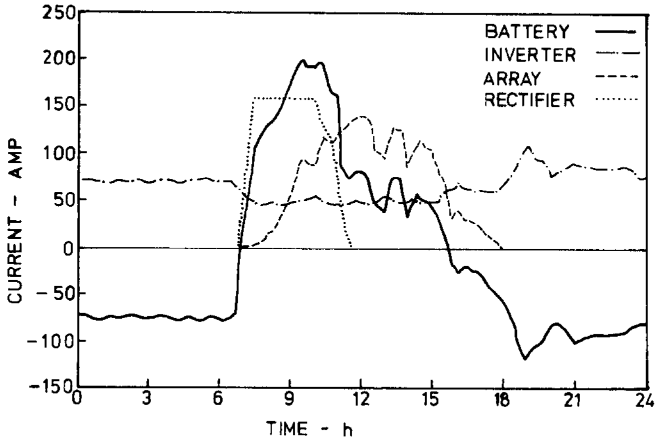

Fig. 9. Diurnal d.c. current flow in power generator on Coconut Island.

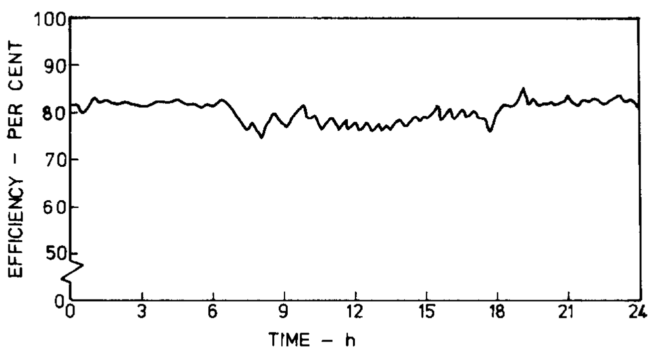

Fig. 10. Diurnal efficiency of inverter in power generator on Coconut Island.

The diesel charger reduces its charge current at 10.00 h, and eventually stops at 11.30 h. On the other hand, the array continues charging, reaching a peak output around noon and then reducing to zero at sunset (~18.00 h). From this time, the battery supplies all the inverter current. The diurnal plot of inverter efficiency (Fig. 10) shows that values higher than 74% are achieved.

Further analysis of the data is required in order to evaluate the system efficiencies, solar fraction, etc., though present indications are that the monthly solar fraction is around 0.5. This high value is due to the fact that the demand is not yet at its design level.

Conclusion

The PV–diesel hybrid power station provides an electricity service comparable with that received by urban dwellers and considerably enhances the quality of life on Coconut Island. There is a limitation on the use of heating appliances, but the effect of this is minimal since alternative heating is available by gas. The social impact of this system will be a significant factor and will be considered along with technical and economic factors in the ultimate evaluation of the system. The client is actively pursuing the installation of similar systems on the remaining 14 inhabited islands in the Torres Strait.

Acknowledgements

The author has reported on a design of a power supply to which a large number of people and organizations have contributed. In particular, the work of the Government Inter-Departmental Project Committee is acknowledged. This Committee was set up on the initiative of the Queensland Department of Community Services and Ethnic Affairs and has as its objective the development of the concept of the Remote Area Power Station. The Committee included representatives from the Departments of the Coordinator-General, Works and Mines, together with the Queensland Electricity Commission. Further, it is acknowledged that the design to meet the specified performance was carried out by Westinghouse/Integrated Power Corporation. Finally, the author thanks the Department of Community Services and Ethnic Affairs and the Coordinator-General for permission to publish this paper.

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