SIMULATION OF A STAND-ALONE PHOTOVOLTAIC POWER SUPPLY WITH BATTERY STORAGE.

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ABSTRACT

Telecom's programmed expansion in the use of solar power has required a reappraisal of the operation and matching of power system components within our remote area power supplies. A solar, stand-alone, power supply consists of a photovoltaic array, a series regulator and a storage battery. The solar array has an optimum load into which it can deliver its maximum power but this varies with solar insolation and temperature. Similarly the battery offers a load to the array that varies with its state of charge and temperature. Therefore the interconnection of these power system components cannot be designed to have the array and battery matched under all conditions.

This paper determines the degree of mismatch existing between the solar array and the storage battery by simulating the power supply operation. Three types of regulator are assessed - a series regulator, a battery voltage temperature compensated regulator and a maximum power point tracking regulator. Models of the power supply components are derived that include many second-order effects such as temperature coefficients and parasitic resistances. These have a small but significant effect on the simulated performance of the power supply. It is shown that the temperature compensated and maximum power point tracking regulators can improve the power supply performance when compared to the series regulator.

INTRODUCTION

Stand-alone power supplies that generate electrical power from solar energy are preferred for most of Telecom Australia's remote area communications equipment with load ratings below 300W. A photovoltaic array generates the electrical power for the equipment load and stores excess energy in a battery. The storage battery, generally a lead/acid type, provides continuous power to the equipment load overnight and during periods of low solar input. The programmed expansion in the use of solar power by Telecom has required a reappraisal of the operation and matching of power system components within these remote area power supplies.

A schematic diagram of the remote area photovoltaic power supply is shown in Fig 1. The solar array has an optimum load into which it can deliver its maximum power but this varies with solar insolation and temperature. Similarly the battery offers a load to the array that varies with its state of charge (SOC) and temperature. The regulator is a voltage-sensitive switch that disconnects the array from the battery to prevent overcharging. The interconnection of these power system components cannot therefore be designed to have the array and battery matched under all conditions.

This report determines the degree of mismatch existing between the array and the battery by simulating the power supply's operation. Two, improved regulator designs are investigated that alleviate the array-battery mismatch.

POWER SUPPLY COMPONENT MODELLING

Photovoltaic Array.

The electrical characteristics of a photovoltaic module within an array are modelled by an exponential curve that is fitted to three significant V-I points; (Voc,0) - open circuit voltage, (0,Isc) - short circuit current, and (Vmp,Imp) - maximum power point. Reference 1 derives the module current as a function of the module voltage, and the Sandstrom model (Ref.2) is used to translate the I-V curve for different values of insolation and temperature. Individual solar cell parasitic resistances are represented by a series and a shunt module resistance. The model has been shown to be accurate to within a few percent (Ref.3) for insolation levels up to 2kW/sqm (equivalent to about 2 suns). The maximum error of -4% in the simulation curve occurs at medium to high insolation levels in the constant current region. Fig. 2 shows the simulated I-V curve for a commercial module.

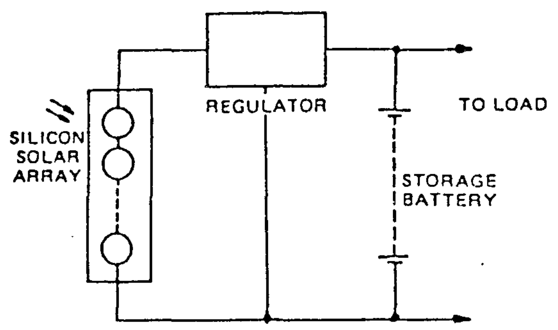

Figure 1.

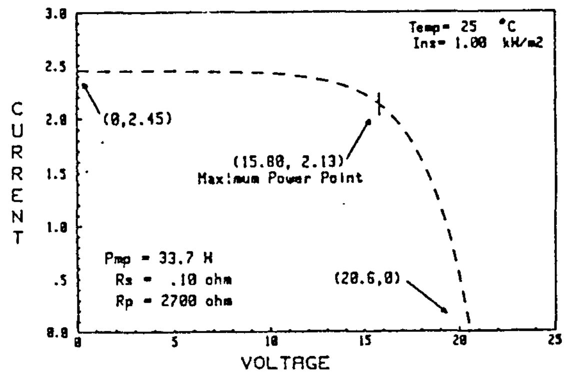

Figure 2.

In operation, the temperature of the cells within a module can be significantly higher than ambient, being affected by such factors as insolation level, packaging and mounting practices and wind speed and direction. Solar cell temperature has been shown to vary almost linearly with insolation (Ref.4) and can be described by :

$$Tcell = Tamb + k*L \qquad \text{..........(1)}$$

where, Tcell = cell temperature (°C)
Tamb = ambient temperature (°C)
k = temperature coefficient (°C/kW/sqm) , typically 25 (Ref.4)
L = insolation level (kW/sqm)

Series Regulator.

The regulator is designed to prevent overcharging of the lead/acid storage battery. The solar array is divided into array groups with each group connected to a separate regulator as shown in Fig. 3. Telecom presently uses a switching type (series) regulator (Ref.5) that senses the battery voltage and switches in and out the solar array group connected to it when the battery voltage reaches preset levels. The regulator switches the array group out of circuit at 2.35 volt/cell and back in at 2.25 volt/cell. The voltage sensing hysteresis band is incorporated to prevent array switching instability. Figure 4 shows the effect of incremental regulator operation on battery voltage and current. The total array current supplying the load and battery is therefore a function of the number of regulator/array groups and the on/off state of each regulator. A typical supply with four series regulators is modelled in this work.

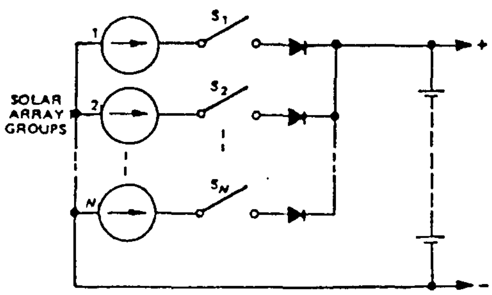

Figure 3.

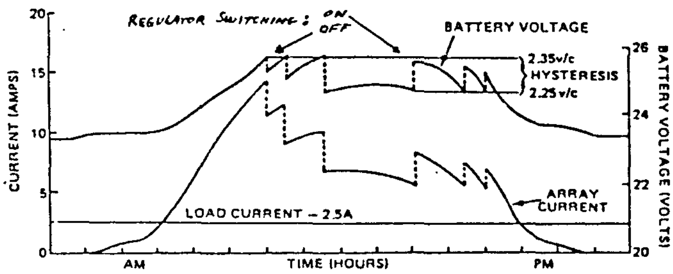

Figure 4.

The switch in the series regulator comprises a Mosfet and a Schottky diode in series. The diode is included to prevent the battery discharging through the solar array group when the array is not illuminated. The Mosfet is modelled by a switch and a temperature dependent series resistance. The diode is modelled by a conduction voltage of 0.4 volts. The regulator voltage drop is described by eqn.2:

$$Vreg = Ig * Rd*(T1 + T2*Tamb) + 0.4 \qquad \text{..........(2)}$$

where, Vreg = regulator voltage drop (volts)
Ig = array group current (amps)
Rd = regulator series resistance (ohms)
T1,T2 = coefficients in the mosfet series resistance equation

Battery.

The terminal voltage of a lead-acid battery is a function of many parameters including charge/discharge rate, charge/discharge history, state-of-charge (SOC), temperature and age. In this paper, battery history and age effects are not included. A simple battery model is used here by fitting a piece-wise linear curve to a typical charging characteristic (Ref.5) of a pasted plate cell at 25°C, as shown in Fig. 5. The straight line approximation introduces a maximum voltage error of 0.015V (<1% of cell voltage).

The charge curve in Fig. 5 is only applicable at one battery temperature and one charge rate (value given in terms of the "C" rate = current in amps required to discharge the battery in one hour) but can be translated for different values of temperature and charge rate (Ref.6,Fig.15.28) as given in eqn.3. The voltage temperature coefficient is stated by battery manufacturers to be about -5 mV/°C. The charge rate parameter Z represents the on/off status of the regulators, where Z=0 corresponds to zero regulators being in the off state (ie. all on).

For SOC <= 90%,

$$Vbcell = 2 + .002278*SOC - .005*(Tempb - 25) - .025*Z \quad .....(3a)$$

For SOC > 90%,

$$Vbcell = 2.25 + .015*(SOC - 90) - .005*(Tempb - 25) - .025*Z \quad .....(3b)$$

where, SOC = battery state of charge (%)
Vbcell = battery cell voltage (Volts)
Tempb = battery temperature (°C)
Z = charge rate parameter (Z=0,1,2,3,4)

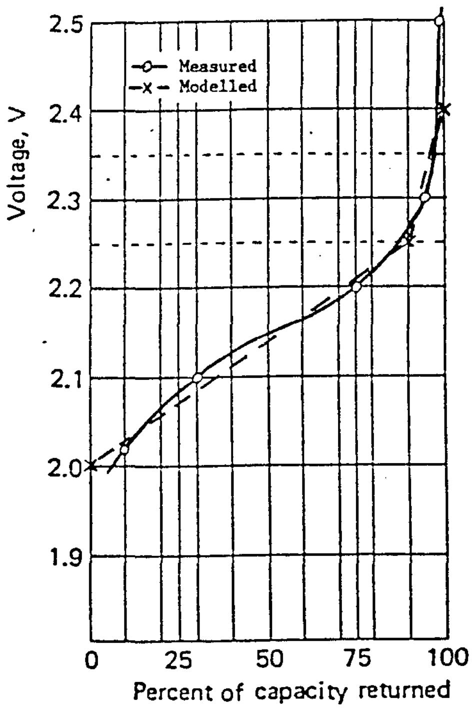

Figure 5. Battery charge curve and modelled characteristic for 500AH pasted plate cell at C/50 charge rate and 25°C.

The battery coulombic efficiency (Amp.hours in to Amp.hours out) is not 100% as the charging process has gassing losses. Gassing is caused by the electrolysis of water within a battery which is nearly fully charged. Coulombic efficiency is very high (>95%) for SOC levels up to 80-90%, after which efficiency drops at a rate dependent on battery type. Ohmic losses can be neglected due to the low charge rates encountered (< C/15 max.). For this simulation the coulombic efficiency eff(ch) is modelled by:

$$eff(ch) = 1 \quad , \text{for } SOC < 90\% \quad ....(4a)$$

$$eff(ch) = (110-SOC)/20 \quad , \text{for } SOC >= 90\% \quad ....(4b)$$

The change in battery SOC is a function of the charge/discharge current:

$$\Delta SOC = 100 * Ibatt / Cbatt \qquad ....(5)$$

where, ΔSOC = battery SOC rate of change (%/hour)
Ibatt = battery charge/discharge current (Amps)
Cbatt = battery capacity (Amp.hours)

The battery has a large thermal mass, which can result in a substantial difference between ambient and battery temperatures. Experimental battery temperature data has been collected at a test site in Innisfail. Analysis of this data has shown the battery temperature variation for a 90Ah battery in a vented enclosure in the shade can be modelled by:

$$\Delta Tbatt = .04*(Tamb-Tbatt) \qquad ....(6)$$

where, ΔTbatt = battery temperature rate of change (°C/hour)
Tbatt = battery temperature (°C)
Tamb = ambient temperature (°C)

Load.

The load for the power supply is the communications equipment, which for most systems can be modelled by a constant power load (Ref.7).

Climate.

To examine the performance of the power supply, four hypothetical days have been postulated by Kuhn (Ref.8) representing a range of typical Australian environmental conditions in which a solar power supply could be expected to operate. In each case an ambient temperature profile and insolation profile were approximated by half-hourly values. The four types of day examined were:

1) clear, hot, bright and sunny (eg. Alice Springs, dry season)
2) dull, cloudy and cool (eg. Melbourne winter, bad day)
3) clear and sunny but cool (eg. Melbourne winter, good day)
4) overcast and cloudy but warm (eg. Cairns, wet season)

The insolation and temperature profiles assumed for day type 1 are shown in Fig. 6. The profiles are symmetrical about solar noon (12am).

System Sizing.

Sizing methodologies for the design of Telecom's power systems are discussed in detail in References 5 and 9. The array is normalised to the load by defining a peak-to-load current ratio given by:

$$PLR = Isc / I(load) \qquad ....(7)$$

where, PLR = ratio of peak array current to load current
Isc = peak short-circuit array current (at 1kW/sqm) (Amps)
I(load) = load current (Amps)

The load current is a function of the battery voltage as given by:

I(load) = P(load) / Vbatt ....(8)

where, P(load) = constant load power (Watts)
Vbatt = battery voltage (Volts)

The battery capacity is defined here by the depth of battery discharge allowed and the number of days storage to this discharge limit. This definition of days storage is different from the usual definition which is the number of days for the battery to be completely discharged.

Cbatt = Dstor*24*I(load) / (DOD/100) ....(9)

where, Cbatt = battery capacity at nominal discharge rate (Amp.hours)
Dstor = battery storage time to DOD limit at nominal discharge rate (days)
DOD = allowable battery depth of discharge limit (%)

Remote area power supplies have typical battery charge/discharge rates in the range of:

Discharge rate range:	max.	C/150	(Dstor=5, DOD=80%)
	min.	C/960	(Dstor=20,DOD=50%)
Charge rate range:	max.	C/17	(Dstor=5, DOD=80%, PLR=10)
	min.	C/240	(Dstor=20, DOD=50%, PLR=5)

where the corresponding overnight depth of discharge ranges from 1.0% of battery capacity (10 hour night at C/960) to 9.3% of battery capacity (14 hour night at C/150).

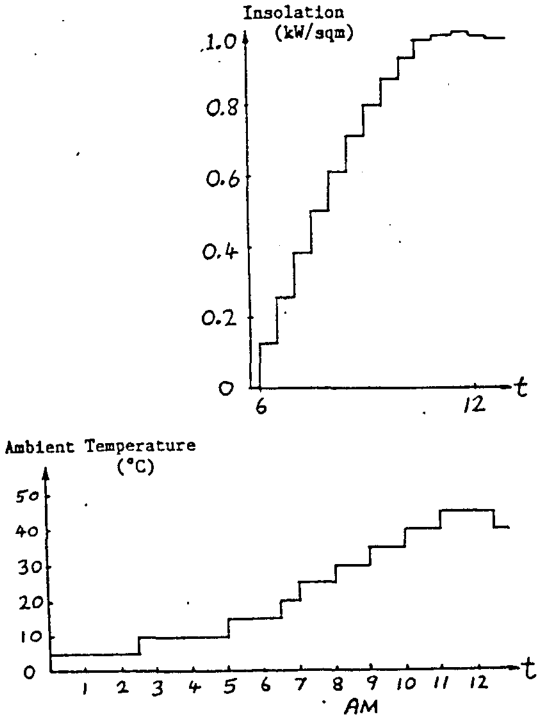

Figure 6. Day type 1 climate

ASSESMENT OF REGULATOR MATCHING PERFORMANCE

The performance of a typical remote area photovoltaic power supply is assessed by comparing the operation of a simulated power supply using a series regulator with one using an ideal maximum power point tracking regulator. The power supply shown in Fig. 1 is simulated using the derived component models. The maximum power point tracker (MPPT) functions as an ideal regulator, tracking the maximum power point of the photovoltaic array and transforming the array power without loss by DC-DC conversion to the battery.

To examine the diurnal environmental effects of changing insolation and ambient temperature levels on the power supplies performance, a simulation was performed using the four hypothetical days described. Simulation results are given in Fig. 7 with the percentage gain in energy yield over a day plotted against battery voltage with day type being a parameter. The series regulator mismatch is less than 5% for most battery voltages. Mismatch exceeds 5% for day type 1 (high insolation levels) when battery voltage is more than 2.25 v/cell (>90% SOC).

To examine the diurnal effects further the battery SOC was simulated for a power supply with PLR=10, Dstor=5, DOD=50% over four consecutive days of the same day type, and the results are shown in Fig. 8 for day type 1. Present system sizing within Telecom uses 10 to 20 days of battery storage (Dstor=5-10 days). Three sets of curves are plotted in Fig. 8 with initial SOC levels of 30%, 60% and 90%. Each set of curves show the SOC resulting from the use of a series regulator (lower line) and an MPPT regulator (upper line).

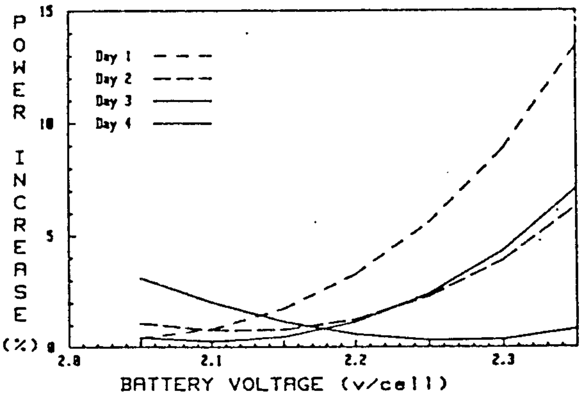

Figure 7.

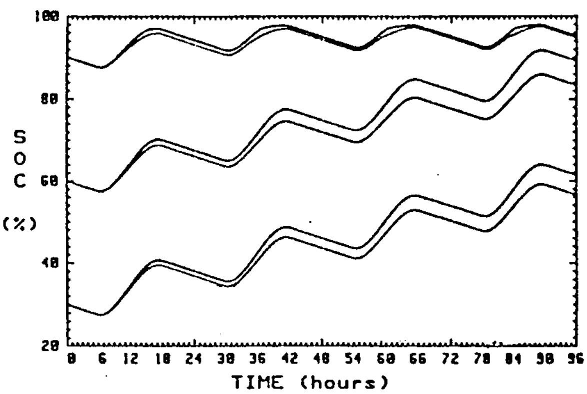

Figure 8.

Results from system simulation show that the mismatch occurring from the use of a series regulator causes a loss in available SOC over the four day period of 19%, 10%, 12% and 22% for day types 1 to 4 respectively for the 60% initial SOC curves. Overvoltage regulation reduces the charge rate when the battery voltage reaches 2.35 v/cell (SOC=96% at 25°C) as shown for the 90% initial SOC curve.

In summary, when battery voltage is assumed constant for simulation purposes the series regulator generally provides a good match (<5% loss in power per day) between the solar array and the battery when operating over a wide range of environmental conditions. However when battery voltage variation is simulated with daily SOC and temperature variations, then the series regulator causes a significant degradation in supply performance, with simulation results using four climate types showing a loss in available SOC of between 10 and 22%. Simulation results are thought to be reasonably accurate taking into consideration the assumptions contained within the component models and the inclusion of relevent second order effects.

REGULATOR DESIGN IMPROVEMENTS

The series regulator can be modified to incorporate battery voltage temperature compensation to improve the overvoltage regulation performance of the power supply. The absence of temperature compensation in the series regulator causes it to misinterpret the battery SOC when the battery is subjected to variations in ambient temperature away from 25°C, and can result in the battery being under or over-charged.

For battery temperatures below 25°C a temperature compensated regulator achieves a slight increase in SOC, compared with a standard regulator. For battery temperatures above 25°C the standard regulator allows over-charging of the battery causing electrolyte depletion due to gassing and possibly excessive corrosion. The future trends for system sizing are to increase array size and decrease battery size, which will cause the battery to be at full SOC for a larger percentage of time. Incorporating temperature compensation into the series regulator will reduce over-charging which could prevent corrosion, allowing an increase in battery lifetime. A series regulator presently costs $80-$100, and the temperature compensation circuitry is expected to increase the regulator price by $20-$40.

The second improvement in regulator design is to use a maximum power point tracking regulator (MPPT). The MPPT uses DC-DC conversion to transform and transfer the array power to the battery. The MPPT improves the system performance by 1) operating the array at the maximum power point, and 2) float charging (constant voltage) the battery when the voltage reaches 2.35 volt/cell. The MPPT should also incorporate battery temperature compensation to prevent over charging.

Inherent circuit losses and non-perfect tracking will reduce the gains in SOC that could be achieved by an ideal MPPT as outlined in the previous section. For instance the gain in available SOC of 23% achieved in Fig. 8 for an ideal MPPT compared to a series regulator, is reduced to 12% by using a 95% efficient MPPT. Investigation of an MPPT regulator by Adams et al (Ref.10) has achieved an efficiency level of 94% for a 48V array, 24V load and 3.3W instrumentation consumption. A commercial MPPT product has become available in Australia that achieves efficiency levels of 95-97% for a 120V array, 48V load with power ratings from 300-1200W. Development of an MPPT regulator by Millnar and Kaufman (Ref.11) has reduced MPP tracking error to less than 1% with a settling time (to +/-2%) of 1 second using microprocessor control of the MPPT operating point.

Installing an MPPT increases the energy transfer efficiency from the solar array, allowing the size of array to be reduced for a given load size (reduced peak-to-load ratio). For a supply with a 200W load and 1,200Wpeak array (PLR=6), an 11% increase in power obtained from an MPPT regulator would allow the array size to be reduced by 10%, saving $1,200 in array costs. Commercial 1,200W MPPT regulators cost about $1,400.

Another aspect of MPPT operation is that savings in photovoltaic array cost from accurate array sizing can be achieved in power supplies by utilising the voltage transforming feature of the MPPT. At present, the photovoltaic arrays for 24V or 48V supplies are sized with 2n and 4n modules respectively (n=number of strings in parallel to achieve required peak array current), as shown in Fig. 9(a). Kuhn has suggested (Ref.12) that by using an MPPT to step-up or step-down an array string voltage the minimum number of modules can be used. For instance, when 5 modules are required to power a 24V supply then 6 modules (in three strings) would be installed. However, the MPPT regulator can be used to step-down the voltage of 3 modules in series, as shown in Fig. 9(b), to reduce the array cost by one module ($330). The savings in array cost can be even greater in 48V supplies when, for instance, accurate sizing requires only 5 modules. In this case a step-up MPPT regulator that transforms the voltage of one module to 48V, as shown in Fig. 9(c), can reduce the array cost by nearly $1000 (3 modules) for a 5 module array that would normally be configured as an 8 module array.

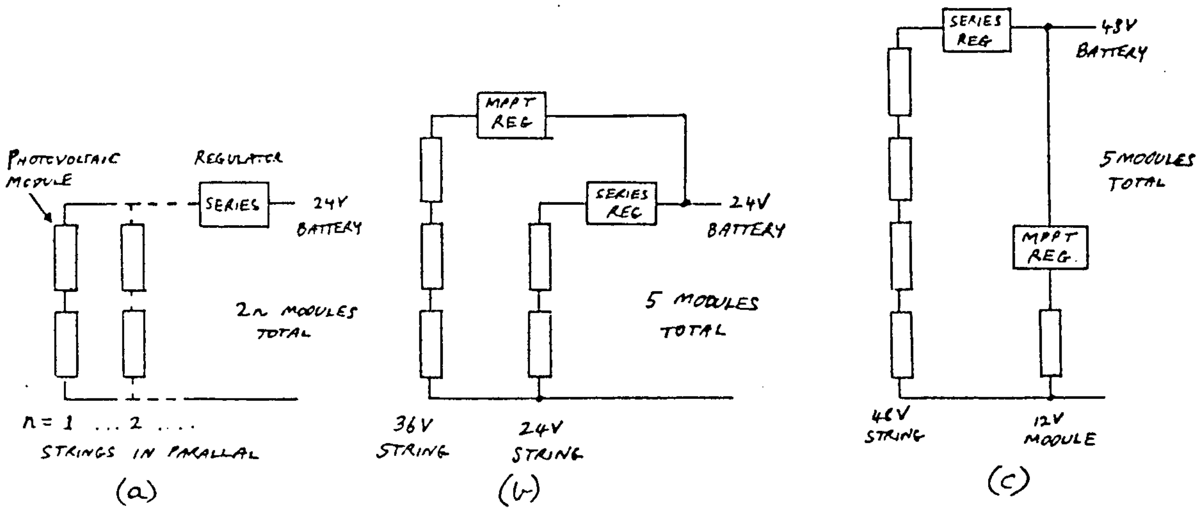

Figure 9.

CONCLUSIONS

Improvements in regulator design have been shown to increase the available battery SOC and to alleviate under/over charging conditions when battery temperature varies significantly from 25°C.

A 5 to 15% increase in SOC is expected from the use of an MPPT regulator, depending on the environmental conditions and the regulators' conversion efficiency. This increase makes the inclusion of an MPPT into a power system economically viable by reducing the required array size.

The performance improvement obtained by incorporating temperature compensation within the regulator is thought to be marginal, except in temperature conditions where significant under or over-charging could degrade system performance and reduce battery lifetime. Consistent over-charging can be expected from a standard regulator in a high temperature, high insolation climate causing electrolyte depletion due to gassing. Telecom is presently investigating and installing batteries with large electrolyte reserves for solar use. The possibility of consistant over-charging causing battery failure due to corrosion needs to be investigated further.

In summary, this report has investigated the simulated performance of a remote area power supply with a photovoltaic array connected to a remote storage battery using a regulator and recommends the incorporation of battery voltage temperature compensation and maximum power point tracking into the regulator's operation.

ACKNOWLEDGEMENT

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