Solar Rectifier

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Abstract - The *Solar Rectifier* is a new and novel product concept for use in solar powered telecommunications sites. The concept includes the integration of switchmode rectifier technology and intelligent monitoring technology into a product that replaces the series regulators and standard rectifier that are commonly implemented at solar sites. The technical performance characteristics of the *Solar Rectifier* are very attractive for network operators, as they can achieve a significant reduction in field maintenance activity and power system life-cycle cost. This paper describes the *Solar Rectifier* concept, and provides two comparative assessments that indicate the benefits of minimising remote site maintenance activity and extending battery lifetime.

I. INTRODUCTION

Internationally, the telecommunications industry has undergone, and still is undergoing, massive restructure. Operators are placing more and more business emphasis on reducing maintenance activity, not only for operational cost reduction but also for reduced staff resource levels. Often, the reduced maintenance effort is reflected in reduced service life of some power system elements.

There are a number of telecommunications operators who maintain large and geographically diverse solar photo-voltaic (PV) powered networks. In Australia, for instance, there are many thousands of PV powered remote sites. Usage and design practices for highly reliable solar power systems have progressed over the last 20 years, with the aim of achieving minimized maintenance effort and system cost. Significant effort has been expended in designing robust series and shunt regulator based power systems to deliver reliable operation. Maximum power point regulators have also been assessed and trailed as an alternative solution. There has also been considerable effort to optimise lead-acid batteries, as the preferred energy storage technology, for shallow cycling solar regimes. However, for these networks there is still a special need to introduce a PV power system that delivers improved life-cycle performance and addresses the performance and maintenance limitations now being faced.

The *Solar Rectifier* is a new and novel product concept for use in solar powered telecommunications sites. The concept was conceived to address the important technical performance issues facing solar power system operators. The concept includes the integration of switchmode rectifier technology and intelligent monitoring technology. The *Solar Rectifier* acts as a *power conversion* interface between the solar PV panels and the battery-load in a solar power system, and replaces the function of the series regulators that are presently in common use. The technical performance characteristics of the *Solar Rectifier* are very attractive for network operators, as they can achieve a significant reduction in field maintenance activity and power system life-cycle cost.

This paper introduces the concepts behind the *Solar Rectifier*. The paper starts with a brief summary of the historical experience with solar PV power systems, focussing on the technical performance issues inherently faced as a consequence of implementing the common type of series switching solar regulators. The paper then introduces the *Solar Rectifier* system, and describes how the important technical performance issues facing operators are addressed.

Two comparative assessments are provided to gauge the likely practical benefits of implementing the *Solar Rectifier* concept. The first assessment involves a power system simulation that compares the efficiency of a standard regulator to a *Solar Rectifier*, over a diurnal cycle, along with the resulting change in SOC of the battery. The second assessment provides a net-present-value analysis that compares the total life-cycle costs of a power system using a standard regulator to those when using a *Solar Rectifier*.

II. HISTORICAL EXPERIENCE

Telecommunications solar power systems in Australia have been in place in significant numbers for over 20 years. From a design perspective, the characteristic battery reserve capacity has reduced from 20-25 days with early systems, to present day battery reserve capacities of 7-10 days. The consequential increase in the ratio of peak solar power to load power has, however, resulted in factors such as system design and regional climate variation having a large impact on battery performance. The battery now experiences larger, but still shallow, daily cycling of the order of 10% of capacity.

In general, network operators have experienced satisfactory performance from their solar power systems. Power system design practices vary substantially between users, and there is a plethora of power system configurations in existence, each one supposedly optimise to best suit the local situation. In particular, the voltage switching levels for the regulators have come under considerable technical scrutiny.

Not withstanding the general satisfaction of network operators, technical concerns have been reported over the last 10 years detailing the occurrence of charging abuse and capacity loss of flooded lead-acid batteries in general use. More recently, there has been an increased use in specific types of valve-regulated lead-acid (VRLA) batteries, primarily in an effort to counter routine maintenance demands with reduced staff levels. However, the legacy equipment and regulation schemes, optimised over many years for traditional flooded cells, are often inconsistent with achieving long VRLA service life in PV applications.

From a network operations perspective, there has been a general acceptance that solar powered sites require appreciable levels of reactive maintenance visits to attend to the origin of low voltage alarms. Often, these visits can be largely unproductive, due to a lack of site information about the cause of the low voltage condition to allow for diagnosis of the correct action and a lack of time to do anything substantial to recover the battery capacity.

The issues associated with traditional PV-battery system design are well known and a detailed examination of the battery performance and optimised charged regimes is outside the scope of this paper. From a battery charge and regulation perspective, the problem issues are familiar:-

Deep discharge or over-discharge

The variability of weather inherently provides conditions for which a site will almost certainly experience a deep-discharge below the nominal 50% SOC design minimum. Permanent capacity loss due to corrosion can result from both extended periods in a deeply discharged state, and also from inappropriate charge current density whilst in a deeply discharged state. Historically, it was network design philosophy and policy that the load should never be disconnected from the storage battery. Therefore, many legacy installations have systems without automatic low-voltage disconnect of the battery. At these sites, the battery can (and some do) completely discharge into the load.

If there is no improvement in insolation to recover capacity from a deeply discharged state, then the only other method of capacity recovery is by maintenance activity. Access to most remote sites requires considerable travel time, and once at site, there is only limited time and opportunity for staff to carefully recovery deeply, or over-discharged battery strings. A slow and careful recharge of a particular site's battery is not consistent with the typical situation where maintenance staff must sequentially visit and recover many remote sites showing low volt alarms. The consequence can be that few sites receive appropriate maintenance recovery charging, and that many affected sites experience a long duration in low SOC with subsequent irreversible capacity loss. Furthermore, once at site, there is no information for staff to determine the actual cause of the depleted capacity. For instance, the battery may have discharged due to persistent levels of low insolation, or may be due to faulty or failed regulators. This may mean that staff perform the best recovery charge that time and circumstances allow, only to return to base to find that within days, the low voltage alarm is again active. This is extremely unproductive and costly.

Equalisation

Daily cycles of discharge followed by high current charging can force the small, unavoidable differences in capacity and charging efficiency between individual battery cells to rapidly lead to diverging cell capacities. Maintenance involving an equalisation charge should preferably be undertaken more often than the typical period of yearly. The result of inadequate equalisation charge occurrences provides a typical condition where cells within a string have marked capacity variation. The consequence is a (high) proportion of sites with less than rated capacity, with commensurately higher risk of battery damage during poor weather periods, and increased reactive maintenance activity.

"Float charge" conditions

A persistent problem with PV-battery systems is the charge methodology when the battery approaches full capacity. A PV array provides a charge current level that is nominally proportional to insolation. With multiple parallel PV array strings, series regulators are used to step the charge current down and up in proportion to the number of strings connected to the battery, using voltage trigger levels within the regulators.

For shallow-cycling regimes, the battery in a typical solar power system spends the majority of time with the battery state-of-charge (SOC) in the region above 80%. A battery operating in this region has characteristics of reduced charge efficiency and increased gassing. For field aged cells, there may be some reduction in charge acceptance. Series regulators that gate the array current to the battery cause significant polarisation and the battery potential quickly reaches the regulator cut-off voltage. As a result, the battery spends a reduced amount of productive charge time within the regulator voltage hysteresis range. The battery takes a longer time to reach 100% state-of-charge, and has increased water usage, compared to a battery charging at the float voltage. Many regulation schemes actually try to maintain the battery in this "switching" state. The consequence is inefficient use of periods of high insolation to bring the battery to full charge, and increased maintenance activity for water topping.

In order to charge the battery in a practical time in this cycling regime, there is a tendency to set the upper voltage trigger level higher than the battery manufacturer's recommendations. The consequence of this action is to void battery lifetime warranty.

Temperature compensation

In general, the use of a constant "float" voltage will cause either over-charging or undercharging conditions when the battery temperature exceeds or is under 25°C respectively. The situation is blurred, in general, as battery temperature varies in both diurnal and seasonal cycles. The general consequence is increased gassing and corrosion at higher temperatures, and reduced capacity and undercharging at lower temperatures.

VRLA batteries

It has been shown that VRLA batteries can be used successfully in shallow-cycling solar regimes [1], and there is now increased deployment of VRLA cells into solar networks. This is primarily to address reduced staff levels to attend to routine water addition and equilisation charging. Most typically, VRLA cells are being used as life-cycle replacement or upgrades into existing solar power systems. However, system designers and operators have yet to gain significant experience with VRLA batteries in this type of application. VRLA technology is inappropriate in some applications, and generally, VRLA cells are not considered as thermally robust as traditional flooded cells. Further, optimisation of the life-cycle performance of the VRLA batteries in PV applications really requires modification of the conventional series regulation scheme. This alone is a substantial onus for geographically large and diverse solar-power networks.

Given that the deployment of VRLA batteries into this type of application will continue for operational rather than technical reasons, there is a need for an improved solar regulation and monitoring equipment.

III. SOLAR RECTIFIER SYSTEM

The *Solar Rectifier* is connected into a telecommunications solar power system as shown in *Figure 1*. The *Solar Rectifier* accepts DC inputs from multiple PV array strings, as well as the conventional AC mains input. The AC mains input is useful during maintenance charging with a portable generator. The rectifier output is connected to the batteries and load using the standard telecommunications architecture. Battery cell and power system parameters are monitored and pertinent data is stored locally. Interfacing for alarm and maintenance function outputs is provided to achieve all the benefits available using intelligent monitoring technology.

The controlled operation of the *Solar Rectifier's* charge profile is achieved using software algorithms developed from significant field experience. An expert system is used to diagnose the state of the power system and determine the required mode of operation. In this way the battery is optimally charged, providing maximised state-of-charge (SOC) within the constraints of the battery manufacturer's specified conditions. When required, the *Solar Rectifier* performs a maximum power point tracking function during part of the daily charging process. Industry acknowledged charging practices, such as limiting the recharge current after a deep discharge till SOC>20%, are implemented in software and fully leverage the integration between the expert monitoring technology and advanced rectifier technology. Where appropriate, equalisation charging is also undertaken on a regular basis using opportunity solar conditions.

Fail-safe operation against rectifier failure is provided for by automatic switching of the solar array(s) through to the battery and load, and by autonomous powering of the battery monitoring function.

The *Solar Rectifier* replaces the series regulators and the standard rectifier equipment that are commonly deployed in telecommunications solar power systems.

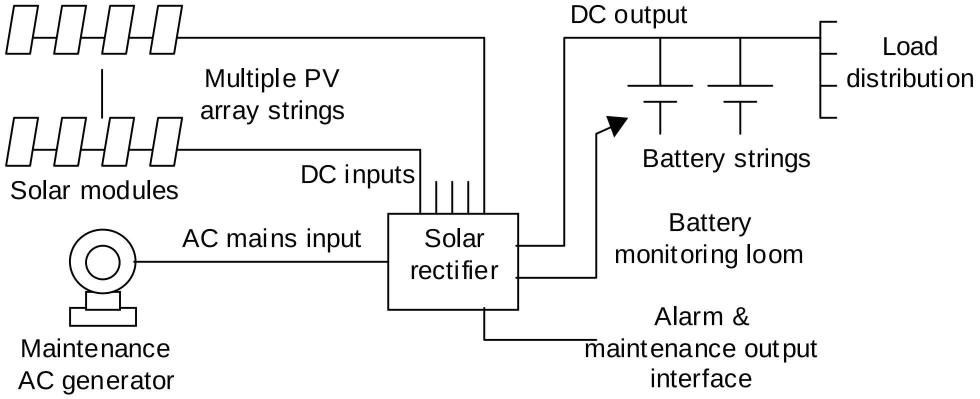

Figure 1: Block diagram of proposed solar power system configuration

A modern telco switchmode rectifier contributes a number of substantial attributes to the *Solar Rectifier*:

- A variety of solar module configurations can be connected, without having to specifically group modules or specifically configure arrays with a given number of multiple panels.

  The actual number of panels used can be the same as calculated in the design brief, thereby optimising the array cost. The PV array string voltage is not constrained to be at the battery voltage, as in existing systems, and so can range from about 36V to 120V, with the lower limit determined by efficiency levels and power rating considerations, and the upper limit determined primarily by staff safety (ELV) considerations.

- The array maximum power point (MPP) can be tracked.

  Up to about 25% of extra energy can be utilised from the PV arrays diurnally for battery charging purposes, compared to existing systems. The extra energy will assist in reducing the number and extent of deep-discharges, and the extent of time taken to reach full state-of-charge. Alternatively, the number of PV modules can be decreased to achieve cost savings.

- Any battery type can be accommodated, within manufacturer specified operating conditions.

  Modern switchmode rectifier's allow software setting of both float and boost (ie. equalisation) voltage and current limit levels, and can control their activation. This broad range of voltage adjustment, along with control of temperature compensation coefficients, allow the rectifier to cope with flooded lead-acid, VRLA and Ni-Cad battery types.

  The rectifier's control of current eliminates the step response normally experienced in existing regulator systems.

- The rectifier buffers the load bus from transient ingress via the solar arrays, and generates no transient upon connection or disconnection of the battery to/from the rectifier-load bus. On-site monitoring contributes a number of substantial attributes to the *Solar Rectifier*:

- Detailed information on an individual cell basis.

  Cell voltage, impedance and current measurement can provide SOC tracking information for the recharge limiting and equalisation functions, and can build up a picture of battery health. Cell interconnects are inherently monitored for integrity.

- Logging of characteristic and event history and, of particular relevance, the last 5-10 days of measured data.

  Historical data assists diagnosis of power system faults and problems, and allows battery end-of-life to be predicted and flagged for programmed replacement.

IV. Power System Simulated Performance Comparison

Using models of a photovoltaic array, regulator, battery and solar regular, it is possible to assess the likely performance benefit of implementing the *Solar Rectifier*. A power system simulation compares the efficiency of a system using a standard regulator to that of a system using a *Solar Rectifier*, over a diurnal cycle, along with the resulting change in SOC of the battery.

The model used for the photovoltaic (PV) array generates a voltage-current curve for different levels of solar insolation and temperature. The model has been previously described [2]. The model includes the effects of parasitic device resistances, and the temperature rise of the PV cells with insolation.

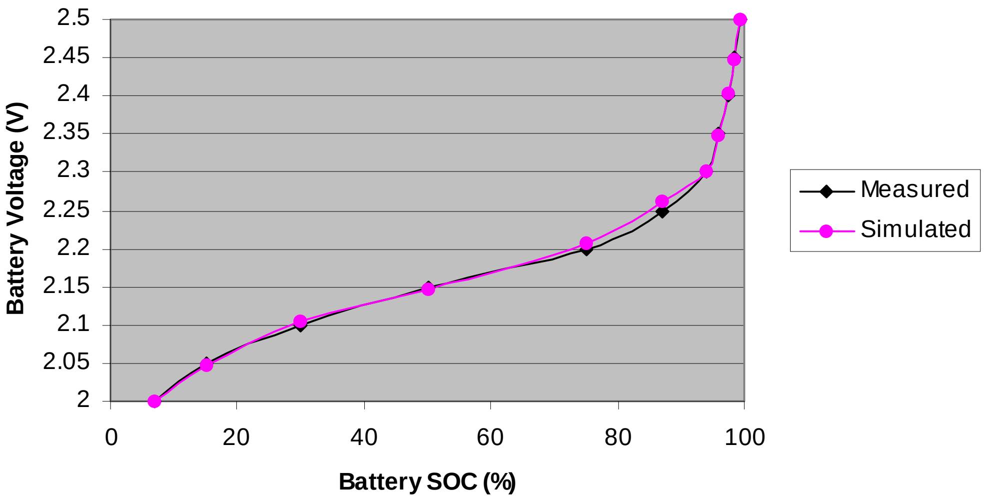

Figure 2: Battery voltage charge profile at C/50 charge rate and 25°C.

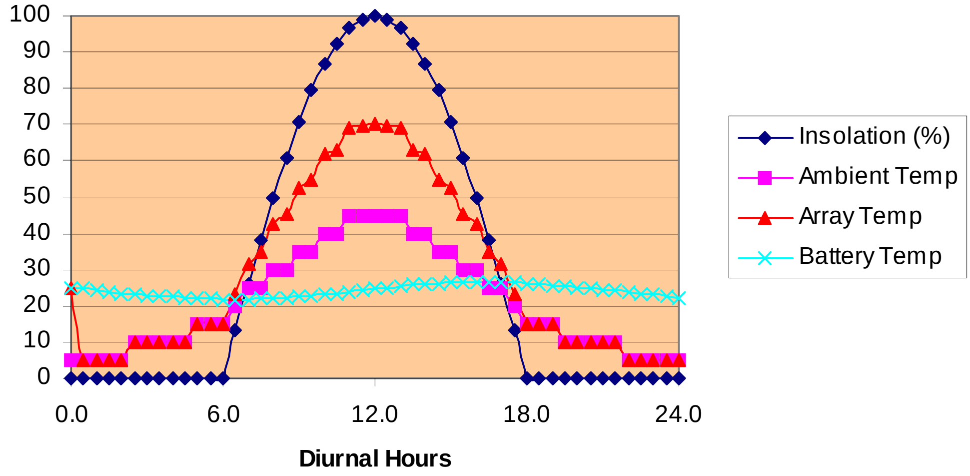

Figure 3: Diurnal environmental profile of a hot sunny climate

A typical solar power system architecture is modeled, containing multiple arrays connected to a battery with each array being connected using a series regulator. The regulator switches the array groups sequentially out of circuit at 2.35 V/cell, and back in at 2.25 V/cell. The regulator comprises a Mosfet controlled switch, and a series diode to prevent reverse current flow at night. The Mosfet has a current and temperature dependent conduction voltage drop.

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. This paper uses a simple curve fit to a typical charging characteristic [3] of a 500Ah pasted plate cell at C/50 charge rate and 25°C, as shown in *Figure 2*. The model is translated for different values of temperature using a coefficient of -5mV/cell/°C. The model is translated for different levels of charge rate using a logarithmic equation and typical Tafel coefficients for charge and discharge.

The battery model uses a charging coulombic efficiency that starts to drop from 100% for SOC levels above about 80%, due mainly to gassing. The change in battery temperature is modeled using a thermal mass equation based on data from a 90Ah flooded lead-acid batteries in the shade in a vented enclosure (thermally transparent).

The *Solar Rectifier* is modeled by a constant power consumption of 10W, and a power conversion efficiency of 95%, when passing power. The constant power consumption accounts for the quiescent power requirements of the converter's switchmode and control circuitry. The efficiency level is typical of modern switchmode power conversion technology. The *Solar Rectifier* is assumed to consume negligible power at night, by operating in a suitable standby mode.

A typical solar power system site is used for the comparison assessment, and comprises a 200W constant power load, a 2kW peak solar array, and two parallel battery strings each of 48V 500Ah. A diurnal environmental profile that is representative of a clear, hot,

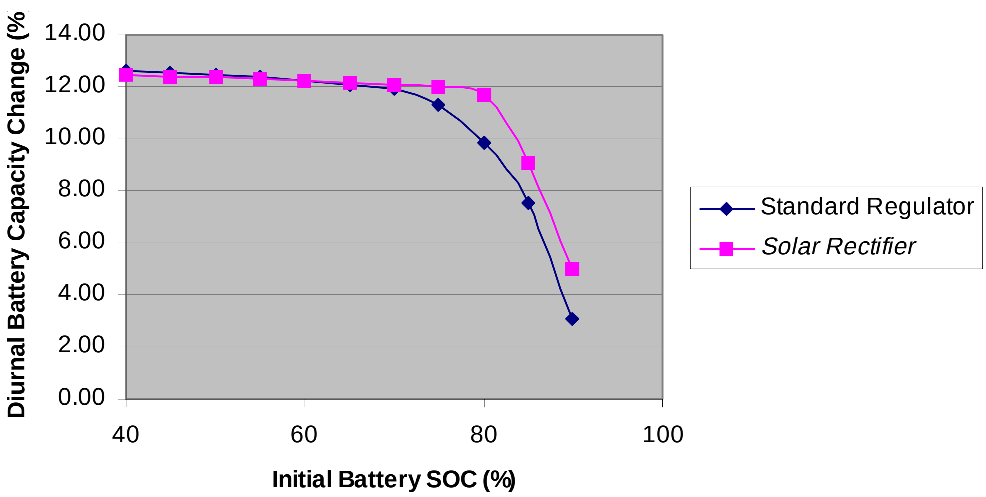

Figure 4: Predicted diurnal change in battery capacity

bright and sunny climate is used, as shown in *Figure 3*. Other hypothetical climates are equally capable of being assessed, to provide a broader appreciation of likely in-service performance.

The modeled result in *Figure 4* shows the predicted diurnal change in battery capacity under the assumed sunny conditions. The model results show that the standard regulator is not as efficient in converting the available solar energy into a gain in battery SOC when the battery's SOC increases above 80%. These results are indicative only, as they are based on a spreadsheet analysis using only 30 minute data-point iterations which is not capable of accurately representing the rapid system changes that occur in a switching regulator system.

V. LIFE-CYCLE COST COMPARISON

This section provides a net-present-value analysis that compares a power system's total life-cycle costs when using a standard regulator to a *Solar Rectifier*.

The life-cycle cost comparison uses a typical 48V solar repeater site with a 200W constant-power load, 10 days autonomous battery operation, and a solar PV peak power to load ratio of 10:1. The battery comprises two 48V battery strings of 500Ah lead-acid batteries. The typical installed battery cost is about AUD$48,000 for valve-regulated lead-acid battery technology.

Standard Regulator Site

Each site has three 20A series regulators, and one 50A standard rectifier, with a combined cost of about AUD$3,000. On average, 2 site visits are made each year, with each visit consuming one staff day at a nominal labour cost of AUD$400. The typical battery lifetime is 5 years.

A site's Net Present Value (NPV) lifecycle cost for the combination of regulator, rectifier and battery components is about AUD$138,000 using an 8% discount rate and an analysis period of 20 years.

Solar Rectifier Site

The comparison site uses a *Solar Rectifier* in place of the standard rectifier and regulators. The *Solar Rectifier* is assumed to have a higher cost than the regulators and rectifier it replaces of AUD$6,000.

The site's equivalent Net Present Value (NPV) lifecycle cost for the combination of *Solar Rectifier* and battery components is shown in *Figure 5* as a function of anticipated battery lifetime. *Figure 5* shows costs where 1 and 2 site visits are made each year, and shows the cost for the standard regulator site with a 5 year battery life.

Although simplistic in nature, the life-cycle cost comparison indicates two important outcomes:

(i) Site capital costs dominate site visit labour costs.
(ii) Site capital cost is very sensitive to battery lifetime, with any increase in battery lifetime providing a cost benefit that quickly pays for any cost increase in regulator/rectifier componentry.

To understand better how the *Solar Rectifier* concept can lead to minimised maintenance activity, and extended battery lifetime, it is important to appreciate the benefits that can accrue as a result of implementing a *Solar Rectifier*.

System benefits to extend battery lifetime:

- Minimising the number and extent of deep discharges.
- Limiting the recharge rate after deep discharge in an automated manner.
- Optimising the float charge profile to reduce the

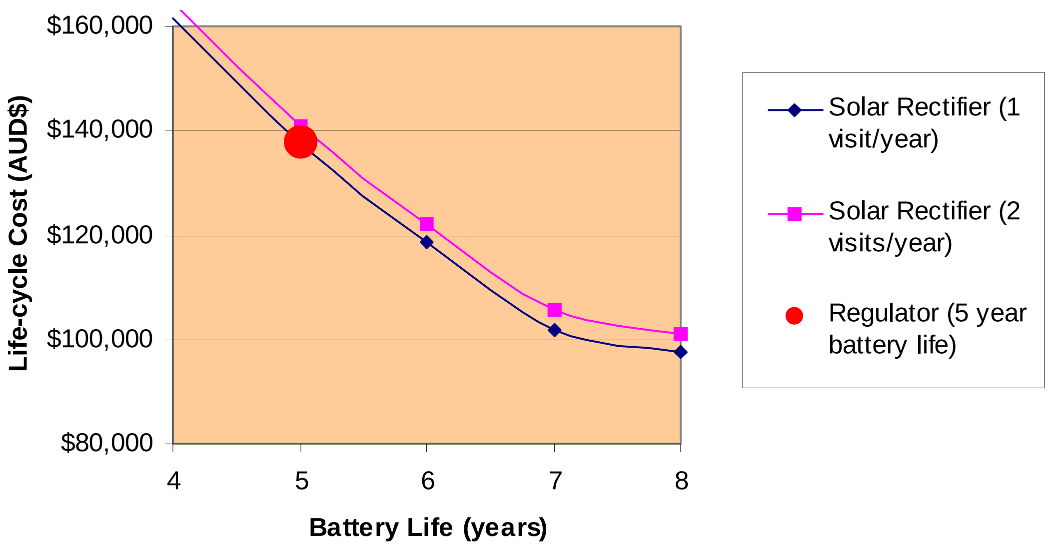

Figure 5: Life-cycle cost of comparative solar sites

severity of gassing and temperature rise.
- Providing continuous taper current charging.
- Introducing temperature compensation of charge voltage.
- Undertaking preventative maintenance on problem cells before good cells are affected.
- Maintaining equalised cell capacities.

System benefits to minimise maintenance activity:

- Optimising the float charge profile, to reduce the need for water top-up with flooded cells, and to operate the battery within manufacturer specified conditions.
- Undertaking automated equalisation charging, where applicable, using opportunity conditions every month.
- Minimising the number and extent of deep discharges that lead to maintenance activity by extracting maximum power from the PV input and efficiently charging the battery.
- Monitoring the battery to pro-actively flag the on-set of a problem and the need for programmed maintenance.
- Monitoring the battery to provide centralised (and local) interrogation and diagnostic assistance.

Other factors that can influence life-cycle cost, but are not included in the above analysis, are:

- The flow-on advantages from changed maintenance operations.
- Increased network mean-time-between-failure (MTBF) and a reduction in mean-time-to-repair (MTTR).

VI. CONCLUSION

The *Solar Rectifier* concept has been described in this paper and two comparative assessments have gauged the likely practical benefits of implementing the concept. Two important benefits for telco solar power system operators that arise from implementing the Solar Rectifier concept have been shown to be the minimisation of remote site maintenance activity, and the extension of battery lifetime.

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