Evaluation of Performance and Reliability for Components of a Linear Hybrid Micro-concentrator System

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Abstract. The Australian National University (ANU), in collaboration with Chromasun Inc., is developing a new hybrid CPV-Thermal (CPV-T) micro-concentrator (MCT) system for concentration ratios up to 30X and producing both thermal and electrical energy. The system design and reliability testing have been integrated as concurrent processes, enabling early and continual optimisation of the concentrator system receiver design. The key feature of this integrated design-test procedure is that carefully selected sets of simple tests can be conducted concurrently with the design of the concentrator module without introducing extensive time delays in the receiver module design phase. Test results provide valuable information that significantly informs the design process and helps to avoid future failures.

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INTRODUCTION

System and component reliability are widely recognised as critical aspects in the design and development of new electronic components and devices. The first qualification standard, IEC 62108 [1], has recently been approved for photovoltaic concentrator systems. This standard defines test procedures that a concentrator module must satisfy in order to guarantee long-term field performance. However, the standard specifies tests confined to the specific purpose of assessing the reliability of the complete concentrator receiver design. The specified tests are time-consuming, and the full test program occurs at the end of the development cycle.

Carefully designed pre-qualification tests conducted during module design development can assist with detecting early failures or identifying potential failure modes, establishing confidence in the entire design process, and helping to improve the final module performance.

THE CHROMASUN-ANU MICROCONCENTRATOR

At the Australian National University (ANU), a new hybrid PV-Thermal micro-concentrator (MCT) system working at a concentration ratio of up to 30X is being developed [2]. This system is very loosely based on the concept of the hybrid PV-Thermal CHAPS system [3], but it is adapted to the domestic and urban rooftop market. It uses single axis tracking based on a Fresnel mirror array.

The MCT system is a fully integrated heat and power solution. The target performance of each module is to simultaneously produce 2kW of solar thermal energy and 500 Wp of electrical power. The MCT system can be integrated into large buildings and domestic residences, as shown in Figure 1.

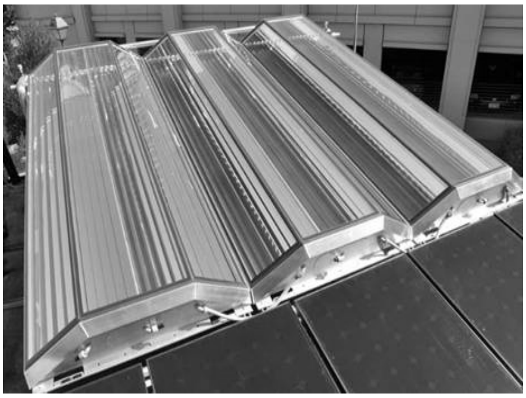

FIGURE 1. Detailed view of the MCT system installed alongside a conventional PV system on the same mounting support.

The CPV-T receiver incorporates modified mono-crystalline, rear-contact, high efficiency silicon solar cells working at a concentration ratio of up to 30X. The solar cells are electrically mounted onto a commercial substrate, as shown in Figure 2, providing a thermal interface between the cell and the heat sink, and ensuring electrical insulation [4]. Each CPV-T hybrid receiver consists of ten PV sub-modules electrically interconnected in series, with cooling water flowing along a channel at the rear of the cells. The sub-modules each contain 30 cells and four bypass diodes. The assembly is encapsulated with clear silicone and thermally connected to the heat sink.

FIGURE 2. A prototype 30 cell sub-module.

Due to the integration of numerous materials with various physical characteristics, each independently subject to varying thermal stresses ranging from short intermittent heat-shocks from passing clouds to long daily thermal cycles, the concentrator receiver is the most complex element in a CPV or CPV-T system.

DESIGN ASSESSMENT OF CPV-T RECEIVER

During the MCT design development, a procedure was established to test the reliability of materials, materials combinations, and progressive design iterations through all stages of the receiver design. This procedure combined several different tests based on the IEC 62108 standard with adaptations designed to detect failures earlier in the design cycle. The testing evaluates components ranging from bare solar cells, materials, and partial assemblies. Each of these groups is subjected to a different sequence of tests, including visual inspection, electrical insulation, electrical performance, thermal cycling tests, and damp heat tests.

A carefully selected set of simple tests can be conducted concurrently with the design of the concentrator module, without introducing time delays on the module design. The test results provide valuable information that help to avoid future failures.

The results of these early component and assembly tests, as well as their value in the assessment of the MCT receiver module design, are presented below.

Thermally Conductive Adhesive Tests

One of the important materials in the MCT receiver is the thermally conductive adhesive that provides a low thermal resistance interface between the main substrate and the heat sink. This material must possess favorable heat transfer properties as well as adequate mechanical properties, since it provides the bond-layer between the two components.

A selection of thermally conductive adhesives was ranked based on considerations including thermal conductivity, mechanical and adhesion properties, chemical composition including toxicity, availability, ease of use, and cost. Thermal cycling and damp heat tests were performed, and the thermal resistance of the samples was measured periodically. The durations of these tests were 3 times longer than those required by the official standard.

The outcome of these tests was the identification of a small number of thermal adhesives with adequate long term thermal performance, along with sustained-mechanical adhesion. A large fraction of the materials sampled were rejected during the intermediate characterisation tests, due to poor adhesion, a significant drop in thermal conductivity, or some combination of the two effects.

Thermal Substrate Tests

To provide an interface between the cell and the heat sink with good thermal heat transfer and sufficient electrical insulation, a commercially available thermal substrate from the power electronics industry was selected.

Dielectric breakdown tests were performed on two different substrate types to determine the capability of the material electrical stand-off characteristic, and how this capability behaves outside the manufacturer’s specified limits. The tolerance margin for lower insulation materials was very limited. However, upon upgrading to a higher insulation standard, a much greater tolerance margin was realised.

Reliability tests were also used to detect materials and workmanship defects. Most importantly, the tests identified areas where the spacing between current-carrying conductors and earth-ground connections were inadequate. This process can also be used to test and optimise the cell mounting electrical design pattern, ensuring connection reliability while also minimising the cost.

Silicone Dielectric Strength Tests

A clear PMDS silicone was used to encapsulate the MCT receiver modules. To optimize the creepage distances between conductive elements in the modules, the dielectric strength of the encapsulant was quantified. Samples with different gap distances between two electrical wires of 50, 150, 200 and 250 microns were built, and the precisely spaced gaps were filled with clear silicone. The samples were then subjected to HIPOT tests at voltage levels up to $2000V_{dc}$. At this voltage, all samples passed the test. When increasing the voltage to 2600 V_{dc}, the 50 micron sample exhibited breakdown, but the 150 micron gap sample, and the others with wider gaps, did not experience breakdown until 17 kV_{dc}.

Initial Prototypes Evaluation

During the MCT design development a number of tests were conducted to provide feedback on reliability and performance. A small selection of these tests will be described in order to illustrate the value of the process.

Cell Damage

Prior to receiver encapsulation the sub-modules are very fragile and can easily be damaged. Although visual inspection and basic V_{oc} tests conducted under one sun return normal results, testing of the 30-cell sub-modules under concentration revealed the possible presence of a number of faults. Visual inspection after high concentration testing identified micro-cracks in a small percentage of the cells. The origin of these faults has not yet been identified, and it is unclear at this stage whether the problem lies with the design, the handling, with the manufacture process, or with the test process. Accordingly, a tool for measuring dark series resistance has been developed, and additional test steps have been introduced to the testing procedure.

Encapsulation Process

The separation layer between the rear surface of the cells and the mounting substrate is very thin. This poses a potential barrier to full and complete silicone encapsulation. Visual inspection of this space following a standard encapsulation procedure revealed an absence of silicone in the void. The expansion and contraction of this air space was suspected to be a contributing factor to early de-lamination failures under extended thermal cycling tests. Recently, a new encapsulation regime has been developed to overcome this problem. This process is described in some detail in a companion paper to this conference. Visual inspection of test samples produced using this new process indicates that the silicone completely fills the space between cell and substrate. Thermal cycling testing of this new method of encapsulation is currently in progress.

Electrical Interconnections

Small prototypes have been manufactured at laboratory level in order to establish anticipated receiver performance. After prolonged thermal cycling, for a period exceeding six months (several times that required by the standards), the integrity of some of the electrical interconnections appeared to be compromised and an increase in electrical series resistance, shown in Figure 3, was detected. The possible failure modes have been identified, and design variations are under way. Possible solutions include alternative materials and a re-design of the electrical circuitry.

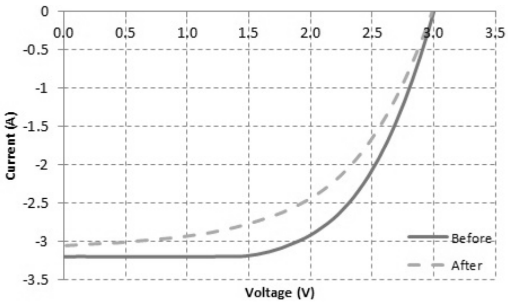

FIGURE 3. I-V curves of one of the initial prototypes before and after the thermal cycling test.

To identify the failure modes causing the degradation seen in Figure 3, the thermal cycling regime was separated into hot thermal cycling (25˚C to 85˚C) and cold thermal cycling (-40˚C to 25˚C). As the receivers are incorporated in a sealed box, and have fluid from a hot water system flowing along the rear of the PV component, it is likely that the temperatures the receiver would experience during operation are within the hot thermal cycling range. Hence, it is more important that the sub-modules are able to withstand the hot thermal cycling than the cold thermal cycling. Figure 4 shows the performance of 4-cell sub-modules through hot thermal cycling. No significant degradation occurred for either encapsulated and unencapsulated samples. Cold thermal cycling tests are underway, and initial results indicate that all thermal cycling degradation occurs in the cold half of the cycle, possibly due to stress on the solder joints.

Electrical Characterisation

Prior to construction of the first full-sized receiver prototype, all the 30-cell sub-modules were tested individually under concentration using a test rig developed by Chromasun. The test rig is shown in Figure 5.

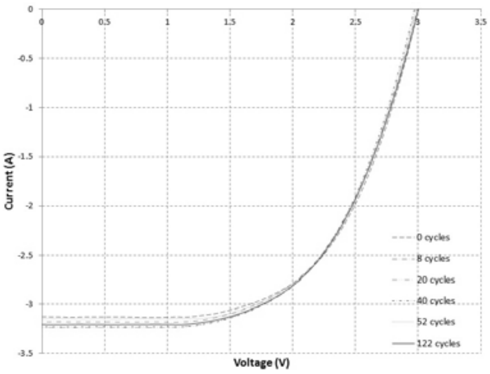

FIGURE 4. I-V curves during hot thermal cycling, showing no significant changes in the electrical performance.

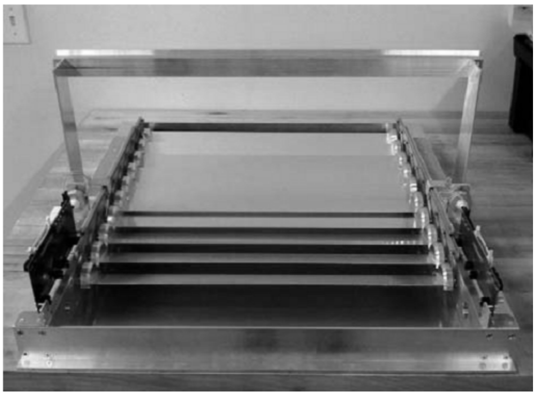

FIGURE 5. The test rig developed by Chromasun using representative mirror sections and full tracking capability.

This testing allowed characterisation of the electrical performance, and enabled sub-modules to be binned according to their respective short circuit current. This provided the best match of modules for each full length receiver.

A typical IV curve generated from one 30-cell sub-module operating at 14 suns (optical) is shown in Figure 6. Abnormalities in the shape of the curve can be used to detect the presence of faults such as cracked cells, faulty diodes, or high resistance electrical interconnections. Analysis of the faults detected from IV curves that were taken under concentration is performed through further visual and electrical tests. The results are fed back through the design and assembly process to improve performance and reliability.

This process will be iterated through prototype development and pilot manufacturing in the commercialisation process.

CONCLUSION

Early evaluation of the physical and mechanical properties of receiver components has been demonstrated to improve the receiver design process and the reliability of the end product. This methodology has been applied to the Chromasun-ANU microconcentrator receiver design. The main outcomes from this experience include the identification of an appropriate selected group of thermally conductive adhesives; the upgrading of the main thermal transfer and cell-mounting substrate between the cells and primary heat sink to a higher insulation standard due to very limited tolerance margins; and the early detection of performance issues in initial prototypes.

The early detection of these performance issues has provided the opportunity for more rapid and reliable design optimisation.

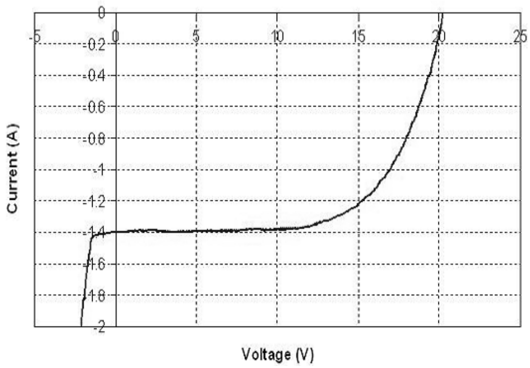

FIGURE 6. A typical IV-curve of a 30 cell sub-module operating at around 14 suns optical concentration.

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