# Modeling the Thermal Runaway Effect in CPV Modules

Marc Steiner, Gerald Siefer, Andreas W. Bett

*Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Heidenhofstr. 2, 79110 Germany*

**Abstract:** In this work current injections into solar cells due to parallel connection within CPV modules are investigated. A current injection into a solar cell increases its temperature. If the current injection is above a certain threshold a thermal runaway is started. The current injection into a solar cell is limited by the short circuit current generated by a string of parallel connected cells. The value of the short circuit current is determined by the number of cells in parallel and by the concentration factor of sun light used in the CPV module. In this work the value of current injection is calculated above which a thermal runaway is triggered. For these calculations a model is introduced and tested with an experimental setup. The model shows a satisfying agreement with the measurement. The model is used to calculate the maximum number of solar cells for which the temperature increase due to current injection is limited to 20 K and a thermal runaway is prevented. This maximum number is presented in dependence of the concentration factor of sun light.

**Keywords:** CPV module, thermal runaway, interconnection, modeling, SPICE.
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## INTRODUCTION

The electrical interconnection of the solar cells in FLATCON®-type CPV modules [1] can be realized in two fundamental ways: in series and in parallel. The optimum choice of interconnection type for a CPV module depends on the electrical characteristic of its components. The advantage of a parallel connection is the compensation of current differences between the solar cells within the CPV module, whereas the drawback of a parallel connection is power losses due to voltage differences. The advantage of a series connection is the compensation of voltage differences between the solar cells and the handicap is power losses due to current differences between the solar cells. In the case of a parallel connection, however, one issue must be solved. This issue is a possible current injection into a solar cell while the module operates near open circuit conditions. The current injection increases the temperature of this particular solar cell. The temperature increase reduces the band gap and increases the dark saturation currents of the cell. This leads to a further increase in current injection which in turn additionally increases the solar cell temperature. In this way, a self-feeding process is started which is often called thermal runaway. A thermal runaway causes high temperature differences within a CPV module which possibly cause damages. A current injected into a solar cell can be prevented by the usage of string diodes [2]. However, the usage of string diodes introduces significant additional power losses in normal operating conditions. Therefore, string diodes should be avoided and a moderate current injection should be accepted. A current injection into a solar cell does not cause a thermal runaway in all cases. A thermal runaway is triggered when the current injection is above a certain threshold. The current injection is determined by the number of cells connected in parallel and by the concentration factor of sun light used in the CPV module. The threshold value of current injection above which a thermal runaway is started depends on the used solar cell and heat sink technology. In this work a thermal runaway model is introduced and tested with experimental data. The thermal runaway model is used to determine a limit number of parallel connected solar cells depending on the concentration factor used within the CPV modules. This limit is calculated for the scenario with the highest risk of causing a thermal runaway. This worst case scenario consists of a number of solar cells connected in parallel working at open circuit while one solar cell is completely shaded. The resulting recommendations are only reliable for the used solar cell and heatsink technology, but the model can be adapted for other CPV technologies.

## MODELING APRROCH

A common approach to calculate the JV characteristic of a triple-junction cell at different temperatures [3] is to apply the two diode model. In this manner every sub cell is simulated by two diodes and a current source. A lumped series resistance completes the electrical circuit. The JV characteristic of such an electrical circuit is calculated by a SPICE network simulation [4]. The temperature dependence of the dark saturation current is implemented using the equations found by Reinhardt et al. [5] and Varshni et al. [6]. This approach to set up a SPICE network model which calculates the JV characteristic of triple-junction cells at different temperatures is described in more details in [7].

In Figure 1 the calculated JV characteristic of two parallel connected solar cells is shown exemplarily. Initially both solar cells are illuminated and operating at 300 K (a). Then, one solar cell is completely shaded. The shading of one cell halves the current density and reduces the open circuit of the string of parallel connected cells. The resulting JV curve (b) and the JV curve of the shaded cell (c) are additionally presented in Figure 1. If the two parallel connected cells are operating at open circuit the shaded cells operates at a negative current. This operating point $J(V_{OC})$ of the shaded cell is marked by a cross (c). The negative current means a current is injected by the illuminated cell into the shaded one. The injected current increases the temperature of the cell. The increased temperature of the shaded cell changes its JV characteristics and thus the JV curve of the string of parallel connected cells. The working voltage of the shaded cell marked by a cross is lowered and the negative working current is increased. This results in a further increase in current injection into the shaded cell which in turn increases its temperature (d). A self-feeding process called thermal runaway is started. This thermal runaway is not stopped until the maximum possible current injection is reached. The maximum current injection is the short circuit current density generated in the string of parallel connected cells. This short circuit current density is determined by the number of solar cells in parallel and by the concentration factor of sun light used in a CPV module.

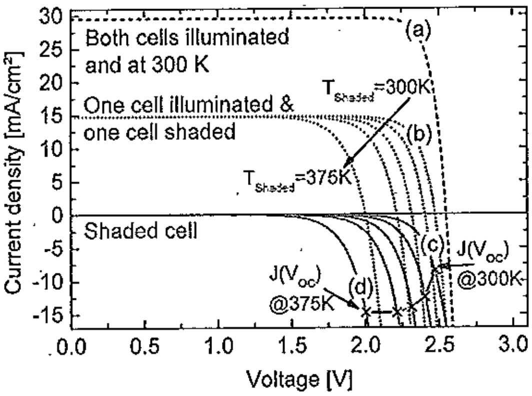

**FIGURE 1.** JV characteristic exemplarily calculated for a string of two parallel connected solar cells operating at the same temperature of 300 K (a). If one solar cell is shaded the current of the string is halved and the open circuit voltage is reduced (b). If the string operates at open circuit a negative current is running through the shaded cell (c). This negative current is marked by a cross. The negative current increases the temperature of the shaded cell which in turn increases the negative current (d). The temperature of the illuminated cell remains constant at 300 K.

The JV characteristics shown in Figure 1 can be calculated by a common SPICE network model [8]. The calculation of the thermal runaway itself was done in this work in an iterative manner:

1. Calculate JV curve of string of parallel connected cells while one cell is shaded at initial temperature $T_i$.
2. Determine the working voltage of the string of parallel connected cells $V_{Working,i}$.
3. Determine current injected $J_{inj,i}$ into shaded cell at $V_{Working,i}$.
4. Calculate temperature $T_{i+1}$ of shaded cell due to injected current.
5. Repeat steps 1 to 4 until $T_i = T_{i+1}$ and $J_{inj,i} = J_{inj,i+1}$, resp.

The steps 1, 2 and 3 can be performed with the SPICE network model. The step 4 requires the resulting solar cell temperature depending on the injected current density. This dependency was determined with the experimental setup shown in Figure 2. A lattice matched triple-junction solar cell mounted onto a copper heatsink was glued on a glass plate. In this way the same conditions as in FLATCON®-type CPV module are realized. The glass plate was arranged in distance from the ground. In this manner heat transfer is mostly performed by convection and radiation similar to the heat transfer of CPV modules. A power supply was connected to the solar cell injecting a fixed current into the solar cell. The injected current increases the temperature of the solar cell which is estimated by a Pt100 sensor located on the heat sink.

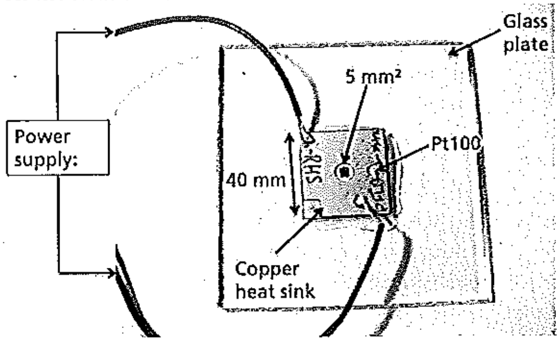

**FIGURE 2.** Experimental setup used to determine the dependency between solar cell temperature and current injection. The lattice-matched triple-junction solar cell is mounted on a copper heatsink, which is glued to a glass plate. A power supply connected to the cell injects a fixed current into the cell. The resulting temperature increase is estimated by a Pt100 sensor located on the heat sink.

In this manner, the dependency between solar cell temperature and current injection shown in Figure 3 was determined. Over the investigated range of injected current density a linear dependency was found. This dependency is implemented into the model by the linear fit shown in Figure 3. For a maximum injected current density of 55 A/cm² a temperature increase of about 125 K was found. For verification of the thermal runaway model the same experimental setup is used. However, this time the power supply applies a fixed voltage to the solar cell instead of a fixed current. Again the resulting temperature of the solar cell is estimated with the Pt100 located on the heatsink. When an applied voltage of about 3.14 V is reached a thermal runaway is triggered in the solar cell and the temperature steeply increases. The thermal runaway model predicted the thermal runaway to happen at an applied voltage of 3.1 V. This shows a satisfying agreement of measurement and model.

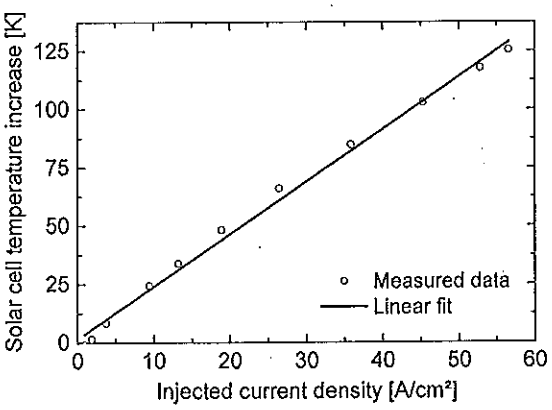

**FIGURE 3.** Measured dependency of solar cell temperature increase and current injected into the solar cell by a power supply. This dependency is implemented by a linear fit into the thermal runaway model.

## RESULTS AND DISCUSSION

The previous chapter described a current injection into a solar cell as a starting point of a thermal runaway. The conditions necessary to cause a current injection into a solar cell are:

1. Parallel connected cells without string diode.
2. Open circuit voltage of one cell lower than the working voltage of the string.

These two conditions do not trigger a thermal runaway in all cases. A thermal runaway is only triggered when the current injection is above a certain threshold. The maximum current injection depends on the number of solar cells in parallel and on the concentration factor of sun light used in the CPV module. The threshold itself depends on the JV characteristic of the individual cells and on the technology of the used heatsink. For the calculation of this threshold a thermal runaway model was set up as described in the previous chapter. The highest risk to cause a thermal runaway is a string of parallel connected cells operating at open circuit condition and one of the cells is completely shaded. In this scenario a current is injected into the shaded cell. Therefore, the temperature of the solar cell is increased. If the current injection is low the temperature increase is low, whereas a high current injection causes a high temperature increase and possibly triggers a thermal runaway. The resulting temperature increase of the shaded cell was calculated with the thermal runaway model. This calculation of the thermal runaway model was used to give recommendations for the design of CPV modules. A limit number of solar cells connected in parallel within a CPV module for a distinct concentration is determined. This limit number of parallel connected cells prevents a temperature increase in a shaded cell above 20 K and thus a thermal runaway in the worst case scenario. This calculation is done for a string of parallel connected cells at open circuit while one cell is shaded. Figure 4 shows the calculated dependency of used concentration factor of sun light and the recommended limit number of solar cells in parallel. Note that the data is only reliable for the used heat sink and solar cell technology, but the model is adaptable to other technologies.

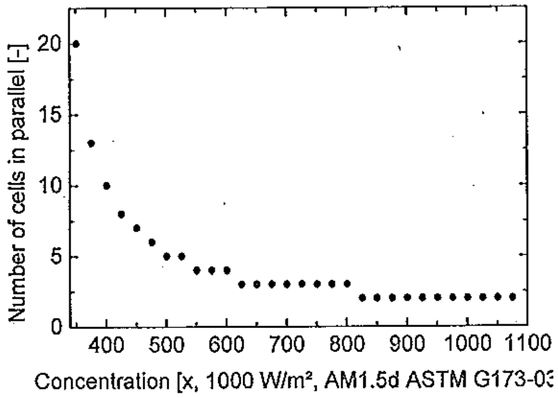

**FIGURE 4.** Recommended maximum number of parallel connected solar cells calculated for a distinct concentration. The numbers are calculated for a string of parallel connected solar cells working at open circuit while one solar cell is completely shaded. Note that the data is only reliable for the

used heat sink and solar cell technology, but the model is adaptable to other technologies.

## CONCLUSION

In this work a model to calculate thermal runaway effects in CPV modules is introduced. The model was tested with an experimental setup with satisfying agreement to the measurement. The thermal runaway model is used to calculate the resulting temperature increase due to current injection into a shaded solar cell while a string of parallel connected cells is at open circuit. In this manner, recommendations for the maximum number of parallel connected solar cells are determined. The calculated maximum number of solar cell limits the temperature increase due to current injection and prevents a thermal runaway. The presented recommendation gives the maximum number of solar cells, which can be connected in parallel in a CPV module in dependence of the used concentration factor of sun light.

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