TEMPERATURE DRIFT CORRECTION FOR FAST LOCK-IN INFRA-RED THERMOGRAPHY

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ABSTRACT: This paper presents simulations of Lock-in Thermography (LIT) measurements performed under non steady-state conditions. The errors caused by temperature drift are compensated by a simple correction formula based on the measurement of the temperature drift image. The effect of this correction has been studied with point, line and extended heat sources, corresponding to the shapes of shunts and non-defect regions. This study shows that the drift-induced error is basically a baseline shift of the in-phase signal to negative values. The relative shape of the signals and the spatial resolution are not significantly affected by temperature drift-induced errors. Results validate the correction method and its effectiveness in eliminating errors from LIT data, which are measured before thermal equilibrium has established.
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1 INTRODUCTION

Infrared Lock-in Thermography (LIT) is a well-known characterization tool for the investigation of solar cells. In this technique, a solar cell is periodically excited by light irradiation or by an external power supply, and its oscillating surface temperature is recorded by an infrared camera. Measured data are averaged over many cycles to increase the sensitivity for detecting shunts or other bad regions of solar cells, which produce more heat as compared to rest of the cell [1]. This is a relatively slow technique, which is a main limitation if LIT should be considered as an in-line tool in solar cell production. For detecting strong shunts, LIT measurements can be performed within a few seconds, which would be feasible for in-line application. However, there is still another problem for implementation of fast lock-in investigations. The whole numerical evaluation formalism of LIT works under the assumption that the measurement is performed under "quasi steady-state" conditions [1]. Hence, it is assumed that the mean temperature of the sample does not change during the LIT measurement. In reality, however, at the beginning of each LIT measurement the mean sample temperature always increases during a certain initial heating phase, until, after a certain thermal relaxation time, it reaches a stable value. Hence, at the beginning of each LIT measurement the sample undergoes a certain temperature drift. The thermal relaxation time mainly depends on the surrounding condition, hence on the heat transfer resistance between the sample and the surrounding medium. Typical thermal relaxation times for solar cell investigation are in the order of tens to hundreds of seconds, which is more than the aspired duration of in-line LIT-measurements. If nevertheless the usual lock-in evaluation methods are applied to such short-time measurements, certain errors in the results have to be expected, unless this temperature drift is anyhow avoided or compensated. Some methods have been proposed in literature for this task. Wu [2] has proposed to start a continuous cooling along with pulsed heating or to preheat the sample up to equilibrium temperature to minimize thermal relaxation time. This solution is difficult to realize in actual practice. It has been realized that the solution should better be analytical or numerical (software-based solution) rather than minimizing this time (hardware-based solution). Mangold [3] explicitly regarded the initial temperature drift by fitting the measured temperature trace with an oscillating function superimposed to a slowly varying function. The limitation in this approach is that this method requires a relatively high numerical expense. An alternative method had been proposed by Breitenstein and Langenkamp [1], who presented a simple correction formula, based only on the measurement of the temperature drift image, which is the difference between the IR images before and after a LIT measurement. This formula was derived from a 'Gedankenexperiment' (mind game), based on the assumption of a linear temperature ramp of a homogeneous heat source in the initial heating phase. It was predicted that this formula would also remain valid for the realistic case of a non-linear (usually exponential) temperature increase and local heat sources.

In this paper, we will present a realistic finite element simulation of the initial heating phase for different geometry of shunts in solar cells. From these simulations, the errors caused by the initial temperature drift are calculated, and the validity of the numerical temperature drift compensation method proposed in [1] is checked. A commonly available circuit simulator 'PSPice' [4] has been used for simulating the electrically converted 2-dimensional finite element thermal model of this problem [5].

2 THEORY

The aim of LIT is to evaluate the oscillating part of temperature signal from the noise by averaging over many cycles. Mathematically, this process can be written as [1]

\[ S = \frac{1}{t_{int}} \int_0^{t_{int}} F(t) K(t) dt \]  \hspace{1cm} (1)

where \( S \) is a output signal, \( F(t) \) is a detected signal, \( K(t) \) is a correlation function and \( t_{int} \) is an integration time over which signal is evaluated. Generally, symmetric correlation functions (like sine/cosine or square wave) of the same LIT frequency are used in correlation. The average value of the symmetric correlation function is zero, therefore it leads to the suppression of d.c. part of signal.
For computer implementation, above equation (1) can be written as [1]

\[ S = \frac{1}{nN} \sum_{i=1}^{N} \sum_{j=1}^{n} K_{i,j} F_{i,j} \]  

(2)

where \( N \) is total number of lock-in cycles and \( n \) is digitizing events (samples) per lock in period. It is assumed here that the lock-in periods are synchronized to the digitizing events, and the correlation applies only to complete lock-in periods. The correlation function can be of different type, depending upon the requirement. For the present LIT application, dual-phase harmonic (sine and -cosine) correlation functions are used, since they allow to evaluate only the basic harmonic of the signal, which carries most of the information, while suppressing higher harmonics. Another advantage of sin^-cos correlation is that it can evaluate the phase of signal, which carries important information. In this paper, only sine correlation is considered, which measures the signal component in-phase to the basic harmonic of the periodic (square-shaped) heat introduction. This signal is called the ‘in-phase signal’ (\( S^{0} \)). It provides best possible spatial resolution in images for displaying different point-like heat sources (e.g. shunts in solar cells), while suppressing the effect of a background (extended) heat source [1]. It has been shown that the complementary out-of-phase signal (\( S^{-90} \)) is less affected by temperature drift, since the \( S^{-90} \) correlation function is more time-symmetric [1]. For computer implementation, the in-phase signal can be written in mathematical form as

\[ S^{0} = \frac{1}{nN} \sum_{i=1}^{N} \sum_{j=1}^{n} 2\sin\left(\frac{2\pi(j-1)}{n}\right) F_{i,j} \]  

(3)

This signal has been used in the study of temperature drift correction in LIT. Fig. 1 shows a typical temperature evolution over the solar cell with extended heat source during LIT measurement. It shows that the temperature oscillations get stabilized after some time.

\[ S^{0}_{\text{correct}}(x,y) = S^{0}_{\text{meas}}(x,y) - \Delta T(x,y) \frac{1}{N n^2} \sum_{j=1}^{n} 2\sin\left(\frac{2\pi(j-1)}{n}\right) \]  

(4)

where \( S^{0}_{\text{correct}}(x,y) \) and \( S^{0}_{\text{meas}}(x,y) \) are the corrected and the measured (uncorrected) in-phase images, respectively, and \( \Delta T(x,y) \) is a total temperature drift in each pixel of the image between start and end of the measurement. It is clear from above equation that, as the number of lock-in cycles (\( N \)) increases, the correction term becomes smaller and smaller and the corrected signal become closer to the measured signal, which is expected for long-lasting LIT measurements.

3 SIMULATION

For simulations, a portion of a solar cell is divided into small square-shaped elements, and the thermal properties of each element are modeled by their electrical equivalent circuit, which is finally connected and simulated by the circuit simulator ‘PSpice’ [4, 5]. Simulated results provide the temperature evolution over the solar cell with different shapes of shunts. Generally, a solar cell may have point- and line-shaped shunts, therefore high intensity point and line heat sources, compared to the background heat source intensity, have been considered in simulations. Apart from that, a separate homogeneous heat source study was also considered. This heat source mimics the homogeneous irradiation of light, which will be used as an excitation source in future for non-contacting in-line LIT shunt characterization methods. A heat resistance to the surrounding medium was introduced in the simulation for considering the typical thermal relaxation time. Simulations have been performed with 30x30 elements, which provide a spatial resolution of 1 mm in a region of 30x30 mm. Results obtained through simulations have been processed according to Eqs. (3) and (4) for getting in-phase images, without and with temperature drift correction.

Figure 1: Typical temperature evolution plot in LIT measurements.

For the correction of the in-phase signal for temperature drift, the following mathematical relation was proposed [1]

Figure 2: Temperature evolution with an extended heat source without surrounding heat resistance.
Fig. 2 shows a simulated temperature evolution with a 2.5 Hz homogeneous pulsed heat source distributed over the entire solar cell region, without considering any heat resistance to the surrounding. In all simulations 10 frames per lock-in period were used ($n = 10$). This type of staircase increase in temperature was expected, which is close to actual LIT measurement in the initial phase (Fig. 1). This is the worst case condition to check the validity of the temperature drift correction method. In this case, the measured (uncorrected) in-phase signal was about -150% of the corrected (steady-state) signal maximum, but the corrected signal was very close to zero (-1.5% of the steady-state signal), as expected for an extended heat source. This result validates the correction method and the entire simulation and computation process. This result was independent of the number of lock-in periods ($N$) and the number of samples ($n$).

Now, this correction method has been used to study the effect of the initial heating phase with point and line shaped shunts. Fig. 3 shows the temperature evolution at the point heat source of 2.5 Hz lock-in frequency located in the middle of the sample. A background heat source of same frequency for homogenous heating was also considered in this simulation. The first 6 lock-in cycles were selected for obtaining the uncorrected and corrected in-phase images according to (3) and (4) respectively.

![Figure 3: Temperature evolution over a point heat source](image)

For checking the validity of the correction, the last 6 cycles data at the end of the simulation (shown in Fig. 3) were used to calculate the steady-state image according to (3). The assumed thermal relaxation time constant was 2.4 s here, and in last cycles the equilibrium temperature was reached to an accuracy of around 1%. Fig. 4 shows corresponding corrected, uncorrected and steady-state in-phase images in the same grey level scale. The difference between the uncorrected and corrected images is remarkable; however there is almost no difference between the corrected and steady-state images, which validates the correction as well as the simulation method. In this figure we have selected the contrast and brightness settings so that the differences are clearly visible. The signal maximum is much sharper than expected from Fig. 4, as the profiles of the corrected and uncorrected images across the point heat source are showing in Fig. 5.

![Figure 4: Uncorrected, corrected and steady-state in-phase images with point heat source](image)

Fig. 6 shows the relative error of the corrected and uncorrected profile to the steady-state profile. This error is given in % of the maximum steady-state signal amplitude. It shows that the corrected signal is not completely identical to the steady-state signal, however the residual error is much smaller, which shows the significance of correction method. This result shows that correction is mainly a baseline shift of uncorrected signal.

![Figure 5: Profiles of the corrected and uncorrected in-phase images across a point heat source. The steady-state profile is identical to the corrected one in this scale.](image)

![Figure 6: Difference of the corrected and uncorrected profiles to the steady-state profile across a point heat source, measured in % of the maximum signal value.](image)
Figure 7: Uncorrected, corrected and steady-state in-phase images of a line heat source.

Similarly, uncorrected, corrected and steady-state in-phase images of a line heat source (corresponding to a line-shaped shunt) in a background of a homogenous heat source of same lock-in frequency (2.5 Hz) are shown in Fig. 7. Fig. 8 shows the corrected and uncorrected in-phase profiles across the line heat source, and Fig. 9 shows their difference to the steady-state profile. These results are of similar nature as of point heat source.

Figure 8: Corrected and uncorrected in-phase profile across a line heat source. The steady-state profile is identical to the corrected one in this scaling.

Figure 9: Difference of the corrected and uncorrected profiles to the steady-state profile across a line heat source, measured in % of the maximum signal value.

4 DISCUSSION

Our simulations have shown that the error of Lock-in Thermography experiments caused by the drift of the sample temperature can be corrected after the measurement by using the temperature drift signal. In all cases, the drift-induced error is predominantly a baseline shift of the in-phase ($S^\circ$) signal to negative values. Hence, the relative shape of the signals and the spatial resolution are almost undisturbed by temperature drift-induced errors. It was shown that the correction formula (4), which uses only the local value of the temperature drift caused by the measurement process, is effective to correct these errors. Especially, the drift-induced baseline shift of the in-phase signal is perfectly corrected. In our simulations, we have observed small residual differences between the drift-corrected and the steady-state results, which may be due to the following reasons:

1. Our "steady-state" data were not exactly steady-state yet.
2. Our assumed thermal relaxation time constant (2.4 s) was not large enough compared to the lock-in period (~ 0.4 s). Hence, the dynamic (a.c.) T-modulation amplitude was not small compared to the stabilized T-increase.
3. Small systematic errors in the simulation cannot be excluded because of the finite element size.

Altogether our simulations have shown the validity of the temperature drift correction procedure according to (4) also for local heat sources and non-linear temperature drift.

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REFERENCES