Early thermal aging detection in tin based perovskite solar cell

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A B S T R A C T

Tin-based perovskite solar cells (T-PSCs) are introduced as the next generation of valid and environment-friendly photovoltaic (PV) cells for near-future commercialization. However, there are some issues limiting T-PSCs including their instability, low efficiency, and use of toxic processing solvents. Among all these barriers, instability and early aging under thermal stress conditions are considered as significant challenges to the development of the T-PSCs. In this study, the impact of different temperature levels on the performance of a T-PSC is investigated over time. It is observed that early degradation of the device occurs at higher temperatures. For timely detection of the early aging, an accurate adaptive estimation of the series resistance is obtained in the equivalent single-diode circuit model of the T-PSC. It is shown that the trend of changes in the series resistance is a reliable indication of the aging process in the T-PSC. Finally, a mathematical index is derived for early aging detection based on the relative variation of the gradient from its minimum value in the linear regression analysis. The proposed approach could be utilized for timely detection of early aging conditions and protection of the device from permanent damage.

1. Introduction

Recently, lead-based perovskite solar cell (PSC) has received much attention for its exceptional properties. High absorption coefficients, low exciton binding energies, long carrier diffusion lengths, high carrier mobilities, and tunable bandgaps are some advantages of this kind of solar cell [1, 2, 3, 4, 5, 6]. The PSCs are considered the next generation of solar cells due to their low cost and easy manufacturing procedure. The PSCs’ power conversion efficiency (PCE) reached 26.1% from the initial PCE value of 3.8% in 2009 [7, 8]. Although lead-based PSCs have remarkable advantages, their commercialization is challenging because of the Pb toxicity. Hence, considerable efforts have been devoted to replacing Pb with other non-toxic metals, such as tin (Sn), germanium (Ge), copper (Cu), and manganese (Mn) [9, 10]. Among all these metals, the T-PSCs have shown promising performance. Both Sn and Pb are in the same periodic table group and almost have similar optical and electronic properties [11]. Moreover, a T-PSC has a smaller optical band gap and higher charge-carrier mobility than the lead-based PSC. However, the oxidation of Sn\(^{2+}\) to a more stable Sn\(^{4+}\) species, the easy formation of tin vacancies, rapid degradation at ambient temperature, and dangling bonds on the surface and at grain boundaries are major issues in the T-PSC [12, 13].

The normal aging process is an unavoidable phenomenon of any device or system, in which the performance of the device is gradually reduced over time [14]. This condition is also observable in devices based on nanostructures [15, 16]. On the other hand, early aging can be considered an abnormal or faulty condition in which rapid performance degradation of the system (device) occurs [17, 18]. Like other devices, photovoltaic (PV) cells are also subjected to normal and early aging processes. The aging process depends on PV technology and environmental conditions, and affects the durability and stability of these electrical devices [14, 19, 20, 21]. Moisture, light, oxygen, UV light, and operating temperature are the most important environmental factors which may result in early aging and instability of the PSCs in case of exceeding the permissible ranges [20, 21, 22]. Among these obstructive factors, the humidity and UV light instabilities can be improved by encapsulating and adding a UV filter membrane [23]. However, temperature instability is a significant challenge in T-PSCs, and no desirable solution has been suggested to address this problem until now. Hence, it is essential to distinguish between the normal and early aging processes to detect faulty conditions and prevent any potential damage to the device as soon as possible.

From the structural aspect, different remedies have been proposed to prevent the early aging in the T-PSCs and increase the stability of these devices. Improving the Tin-perovskite crystallinity, T-PSC archi-
tecture optimization, replacement of the MA (methylammonium) cation with FA (formamidinium), and utilization of different additives and co-additives in the absorber layer, and the addition of protective layers to the device have been proposed to increase the T-PSC stability [15, 24, 25, 26, 27, 28, 29]. However, there are few reports regarding early aging detection of the PSCs. Guo et al. investigated the accelerated aging in MAPbI3 PSC caused under illumination of concentrated sunlight [30]. They showed that the photo-stability of the MAPbI3 film is extremely sensitive to the sample temperature, but no index for early detection is suggested in this report. Mahapatra et al. showed that the photovoltaic and electrical characteristics of the PSC change during the aging time [31]. They believed that understanding the device’s electrical characteristics during the aging process is important for the design and development of effective strategies for the fabrication of stable PSCs. Pica et al. investigated the degradation mechanisms of carbon-based PSCs (C-PSCs) under thermal stress [32]. They showed that C-PSCs are stable at temperatures below 50 °C and up to 80 °C with limited operating time, and upon prolonged thermal stress, degradation takes place. They concluded that the main effect of thermal stress leads to a reduction of the shunt resistance, which is attributed mainly to the rearrangement of the interface orientation and interface crystallization.

In this paper, the method of accelerated aging is implemented by applying thermal stress conditions to study the early aging procedure in the T-PSCs. For this purpose, impact of the operation temperature on the performance and early aging of a T-PSC is simulated by excess electron concentration and defect concentration with Shockley–Read–Hall (SRH) recombination in the SCAPS-1D software. It is very common in literature to consider high temperature as a factor of stress condition in PV applications to investigate the early aging procedure caused by undesirable temperature conditions. To investigate the effect of temperature on the PSC performance, two different temperature values of 25 °C and 85 °C are considered. It is observed that high-temperature values cause degradation in the performance of the T-PSC from the PCE, fill factor (FF), and the current-density-voltage (J – V) characteristic aspects. Moreover, higher temperature operating condition results in low stability and early aging of the device. However, at the standard temperature value of 25 °C, the normal aging process occurs over time. Hence, a reliable method is necessary to detect early aging in the T-PSC at the proper time. Here, an accurate and unique single-diode circuit model is developed for the T-PSC, for which a convex optimization approach estimates five unknown parameters: the photocurrent density (J_m), the diode saturation current density (J_s), the series resistance (R_s), the parallel resistance (R_p), and the diode ideality factor (a). The trends of variations of all the five parameters are studied for four different temperature values, including 25 °C, 45 °C, 65 °C, and 85 °C for the 2400 h time interval. It is revealed that the series resistance is a good indicator for detecting early aging in the device. Since aging is a gradual process over time, the gradient variation in the linear regression analysis with respect to its minimum value is considered an early aging fault detection index. The main contributions of this work can be summarized as follows:

1- Unique and precise estimation of the parameters in the single-diode circuit model at any environmental condition for the T-PSC.
2- Comprehensive study on the effect of temperature on the performance of T-PSC over time.
3- Suggestion of a suitable criterion for timely, reliable, and precise early aging fault detection in the T-PSC.

The rest of the paper is organized as follows: The behavior of the T-PSC according to its excess electron concentration and defect concentration and the generation of its equivalent single-diode circuit model are discussed in Section 2. The effect of temperature on the performance of the T-PSC and the mathematical formulation of the early aging fault detection are presented in Section 3. This is followed by remarks on the main conclusions in Section 4.

2. Theory

2.1. Degradation kinetics in PSC

Under stress conditions, excess charge carriers, n, and p, generate, which cause the formation and increase of defects in the PSC [33]. Since the defect increment affects the behavior and performance of the device, the degradation rate of the device parameters can be modeled by monitoring the defect concentration [33, 34, 35]. The kinetics of the excess carrier and excess defect creations are related as follows [36, 37, 38]:

$$\frac{dN}{dt} = an - \beta N$$  \hspace{1cm} (1)

where α and β are the defect creation and annihilation rates related to the material parameters, and their values are assigned according to the defect type. Moreover, n shows the excess concentration of the electrons or holes with exponent ν, and N represents the defect concentration. By considering a relatively short time profile such that β ≪ 1, the annihilation term can be neglected, and the dynamics Eq. (1) can be simplified as [33]:

$$\frac{dN}{dt} = an$$ \hspace{1cm} (2)

An increase in the carrier and defect density changes the material characteristics, the generation and recombination rates, and the built-in voltage at the terminal [33]. Hence, as stated in Eq. (2), there is an interaction between the excess carriers and the defect densities. At the steady-state stress condition and constant generation rate (G), we have:

$$\frac{dn}{dt} = G - B_n n' + \mu E \frac{dn}{dt} = 0$$ \hspace{1cm} (3)

where B, μ, E and ν are the band to band recombination coefficient, mobility, electric field, and exponent of the carrier recombination, respectively [33]. Three different carrier concentration scenarios can be considered for Eq. (2) and Eq. (3). Linear n or p with ν = ν’ = 1 for band-band radiative recombination, nonlinear n with ν = ν’ = 2 to present a Shockley–Read–Hall (SRH) recombination process, and bilinear condition, in which np is replaced by n for nonradiative bi-molecular recombination [33].

In T-PSCs, Shockley–Read–Hall (SRH) recombination is predominant compared to other recombination types due to the large defect density and poor layer quality [39]. Hence, the defect density dynamics for this PSC can be written as:

$$\frac{dN}{dt} = an^2$$ \hspace{1cm} (4)

The discrete form of Eq. (4) for the numerical solution of this equation for each carrier profile results in a different equation:

$$N_i^{(t+1)} = N_i^{(t)} + a \Delta t \left( n_i^{(0)} - n_i^{(0)} \right)$$ \hspace{1cm} (5)

where $n_i^{(t)}$ and $N_i^{(t)}$ are current excess electron concentration and defect concentration values while $N_i^{(t+1)}$ represents defect concentration for the next iteration. Also, $n_i^{(0)}$ is the electron concentration in the perovskite layer in the dark state and it should be noted that $n_i^{(0)} > n_i^{(0)}$ has to be satisfied at all times. One can utilize SCAPS-1D software to solve Eq. (5), in combination with Poisson and charge continuity equations.

2.2. Equivalent electrical circuit model

For precise analysis, optimizing the device structure, fault detection, and monitoring of the performance of the PV systems, a reliable model of the PV cell is required [40, 41, 42]. The simple and accurate $J - V$ characteristic of a PV cell with a single-diode equivalent circuit model is given by:
where $J$ and $V$ are the output current density and voltage of the cell, respectively. The photocurrent density ($J_{ph}$), the diode saturation current density ($J_0$), the series resistance ($R_s$), the parallel resistance ($R_p$), and the diode ideality factor ($a$) are the five unknown parameters. Since the electronic charge ($q$), the Boltzmann’s constant ($k$) and the cell temperature ($T$) are the known values, the thermal voltage ($V_t$) can be defined as:

$$V_t = \frac{a k T}{q}$$

(7)

Therefore, Eq. (6) can be rewritten as:

$$J = J_{ph} - J_0 \left[ \frac{V}{V_t} \left( V + J R_s \right) - 1 \right] - \frac{V + J R_s}{R_p}$$

(8)

At a constant and uniform solar illumination ($S$) and cell temperature, a typical nonlinear $J - V$ curve has three points of interest. The open-circuit voltage ($V(J, V) = (0, V_{oc})$), where the voltage has its maximum value and current is zero. The short-circuit current density ($J(J, V) = (J_{sc}, 0)$), where the current has its maximum value and voltage is zero. The maximum power point (MPP), with ($J(J, V) = (J_{mp}, V_{mp})$). In fact, at MPP the maximum power density $P_{mp} = J_{mp} \times V_{mp}$ of the PV cell is achieved corresponding to the constant and uniform $S$ and $T$. However, the $J - V$ curve of the same PV cell can be varied by the change in environmental variables $S$ and $T$. In other words, the aforementioned three points can be considered as functions of two environmental variables $S$ and $T$. In general, an increment of $S$ results in higher photocurrent generation and higher MPP, consequently. On the other hand, an increment of $T$ leads to lower operating voltage and less power generation.

Considerable investigations have been conducted to extract the five unknown parameters of the single-diode model from the $J - V$ curve [43, 44]. However, parameter estimation is a difficult task due to the high nonlinearity and nonconvexity of the problem. In [45], an adaptive estimation approach was utilized for PV module parameter estimation. Here, this PV parameter estimation method is modified for model identification of the PSCs at any environmental condition, i.e., any $S$ and $T$ values.

First of all, it is assumed that the three points of interest are available from real measurements or computer simulations. By substitutions of these points in the $J - V$ characteristic Eq. (8) and some simplifications, $R_s$, $J_0$, and $J_{ph}$ variables can be written as the functions of $V_t$ and $R_s$ in the form:

$$R_p(R_s, V_t) = \frac{\phi(R_s, V_t) (R_s J_{sc} - V_{oc}) - V_{mp} - R_p J_{mp} + V_{oc}}{J_{mp} - 1}$$

(9)

$$J_0(R_s, V_t) = \frac{J_{sc} - V_{oc} - R_s V_t + R_s J_{sc} / R_s J_{sc} (R_s, V_t)}{\exp(V_{oc} / V_t) - \exp(R_s J_{sc} / V_t)}$$

(10)

$$J_{ph}(R_s, V_t) = \frac{(\exp(V_{oc} / V_t) - 1)J_{sc} - V_{oc} \exp(R_s J_{sc} / V_t)}{\exp(V_{oc} / V_t) - \exp(R_s J_{sc} / V_t)}$$

(11)

where the nonlinear function $\phi(R_s, V_t)$ in Eq. (9) is defined as Eq. (12):

$$\phi(R_s, V_t) = \frac{\exp(V_{oc} / V_t) - \exp((V_{mp} + R_p J_{mp}) / V_t)}{\exp(V_{oc} / V_t) - \exp(R_s J_{sc} / V_t)}$$

(12)

Hence, by the known variables $R_s$ and $V_t$ the other three unknown parameters can be calculated from Eq. (9)–(11). Based on the fact that the derivative of the power with respect to the voltage at the MPP is zero ($\frac{\partial P_{mp}}{\partial J_{mp}} = 0$), an explicit equation with respect to independent variables $R_s$ and $V_t$ is achieved as:

$$\varepsilon(R_s, V_t) = (R_s + R_p(R_s, V_t)) V_t J_{mp}$$

+ $(R_s R_p(R_s, V_t) J_0(R_s, V_t) J_{mp})$

$$- R_p(R_s, V_t) - J_0(R_s, V_t) J_{mp} \exp((V_{mp} + R_p J_{mp}) / V_t)$$

(13)

An objective function ($O$) is defined in Eq. (14) to estimate $R_s$ and $V_t$ corresponding to the solutions of the nonlinear relation Eq. (13).

$$O(R_s, V_t) = \min_{R_s, V_t} \varepsilon^2(R_s, V_t)$$

(14)

The reason for deriving a square function $\varepsilon^2(R_s, V_t)$ is to highlight the importance of the magnitude of $\varepsilon$ rather than its positive or negative value. Obviously, $R_s$ and $V_t$ should be chosen such that $\varepsilon^2(R_s, V_t)$ reaches its minimum value of zero. As discussed in [45], the optimization problem Eq. (14) is highly nonconvex and it has an infinite number of solutions. To address this problem, a constrained optimization problem is established where the inequalities are defined according to the physical limitations of the single-diode circuit model.

The value of the ideality factor represents the dominant recombination type in PSC. The diode ideality factor of a typical PSC is larger than or equal to 1 based on different recombination mechanisms [42]. Therefore, considering Eq. (7) the thermal voltage should be chosen such that $V_t \geq \frac{k T}{q}$. As justified in [45], the $R_s$ value can be varied as in Eq. (15):

$$0 < R_s < \frac{V_{oc} - V_{mp}}{J_{mp}}$$

(15)

Also, it has been proved that the nonlinear inequality $\phi(R_s, V_t) > \frac{J_{mp}}{V_{oc}}$ has to be satisfied. The linear equivalent of this inequality can be derived in Eq. (16) as [45]:

$$V_{oc} - V_{mp} - J_{mp} R_s - \ln(J_{sc} / (J_{sc} - J_{mp})) V_t \geq 0$$

(16)

Based on the above inequalities, a constrained optimization problem can be defined in Eq. (17) as:

$$O = \min_{R_s, V_t} \varepsilon^2(R_s, V_t)$$

subject to

$$y_1(R_s, V_t) = V_t - \frac{k T}{q} \geq 0$$

$$y_2(R_s, V_t) = \frac{V_{oc} - V_{mp}}{J_{mp}} - R_s \geq \varepsilon$$

$$y_3(R_s, V_t) = R_s \geq \varepsilon$$

$$y_4(R_s, V_t) = V_{oc} - V_{mp} - J_{mp} R_s - \ln(J_{sc} / (J_{sc} - J_{mp})) V_t \geq 0$$

(17)

where $\varepsilon \ll 1$ is a very small positive value. An interior-point approach is utilized to convert the constrained optimization problem to the identical non-constrained one. Hence, by introducing the barrier function $\ln(\cdot)$ and the positive constant barrier parameter $\rho$ an augmented cost function is given by Eq. (18):

$$O(R_s, V_t) = \min_{R_s, V_t} \left( \varepsilon^2(R_s, V_t) - \rho \sum_{i=1}^4 \ln(y_i(R_s, V_t)) \right)$$

(18)

It has been verified by [45], that the optimization problem $O$ has a unique global minimizer solution $(R_s^*, V_t^*)$. However, these values cannot be obtained by explicit calculations due to the complexity of the nonlinear objective function. In order to achieve these unknown parameters, two gradient-based adaptive update laws are derived:

$$\dot{R}_s = -k \frac{\partial O(R_s, V_t)}{\partial R_s}$$

$$\dot{V}_t = -k \frac{\partial O(R_s, V_t)}{\partial V_t}$$

(19)
3. Results and discussion

In this study, a reliable index is derived for early aging detection in T-PSC. Since temperature is one of the most effective parameters for the aging of the PSCs, here the aging process is investigated under thermal stress. For this purpose, the performance of the T-PSC over time is modeled by SCAPS-1D software for different temperature values from the solution of Eq. (5). The four key parameters $V_{oc}$, $J_{sc}$, $V_{mp}$, and $J_{mp}$ are achieved from the simulation. Then, the five parameters of the equivalent single-diode circuit model are extracted by the method explained in subsection 2.2 in the MATLAB environment. All the simulations are derived under AM1.5G solar illumination with an incident power density of $S = 100$ mW/cm². For the standard (room) temperature value of $T = 25 \degree C$, the cell parameters calculated by SCAPS-1D are $J_{sc} = 18.03$ mA/cm², $V_{mp} = 0.440$ V, FF = 69.1%, and PCE = 5.49%.

In order to show the impact of the cell temperatures on the early aging process, the PCE variations through time are considered for the standard temperature $T = 25 \degree C$ and the extremely anomalous temperature of $T = 85 \degree C$. The PCE variations at room temperature are the regeneration of the experimental data presented in [113]. Figure S1 in the supplementary material (SI), shows the simulated data together with the experimental data for the T-PSC based on FASnI₃. The simulated results show a close match to the experimental results which confirm the validation of the parameters used in the simulation. The results of the PCE variations for 25 °C and 85 °C temperatures during 2400 h are illustrated in Fig. 1. It is obvious from this figure that the cell has a stable performance with a normal aging process at room temperature. On the other hand, the PCE is dramatically decreased through time at 85 °C for the same cell. More specifically, during the first 2400 h, for $T = 25 \degree C$ the PCE value is decreased from 5.30% to 4.24%, but for $T = 85 \degree C$ the PCE value is decreased from 3.67% to 0.350%. Two major interpretations can be obtained from these results. First, the cell temperature increment leads to lower efficiency and performance. Second, the rate of solar cell degradation increases at higher temperatures. For example, the slope of PCE variation from $t = 0$ h to $t = 2400$ h at $T = 25 \degree C$ is about $-4.37 \times 10^{-3}$ and at $T = 85 \degree C$ is about $-1.38 \times 10^{-3}$. Hence, the rate of degradation at $T = 85 \degree C$ is 3.2 times faster than $T = 25 \degree C$, which indicates early aging at higher temperatures. Moreover, there is an almost uniform rate of degradation at the standard temperature, but the rate of aging is highly increased between 1200 h and 1900 h for $T = 85 \degree C$. In other words, the device’s durability is started to deplete after 1200 h.

The $J - V$ characteristics at $T = 25 \degree C$ and $T = 85 \degree C$ for four different time instants are shown in Fig. 2. It is observed from Fig. 2a that the $J - V$ curves are slightly changed at $T = 25 \degree C$. However, the $J - V$ curves for $T = 85 \degree C$ (Fig. 2b) are completely different with respect to both $V_{oc}$ and $J_{sc}$ values. In order to be more specific in this regard, the $J - V$ data values are reported in Table 1. At $T = 25 \degree C$, the absolute relative variation for $V_{oc}$ is around 1.82% and the absolute relative variation for $J_{sc}$ is around 9.45% for 2400 h time interval. Similarly, the absolute relative variations for $V_{mp}$ and $J_{mp}$ at $T = 85 \degree C$ are 21.85% and 80.9%, respectively. Therefore, it can be concluded that the aging process has more impact on the $J_{mp}$ compared to the $V_{mp}$. In other words, $J_{sc}$ has more variations than $V_{oc}$ through time for both standard and anomalous temperature conditions. Moreover, the aging process has a much faster rate at $T = 85 \degree C$ compared to the aging rate at standard temperature. More precisely, the rate of reduction of $V_{oc}$ and $J_{mp}$ values at $T = 85 \degree C$ are 12 and 8.5 times faster than $T = 25 \degree C$, respectively. Also, a similar result can be achieved for the FF variable as indicated in Table 1. Hence, all these results verify the early aging process at high temperatures.

The variations of the five parameters in the equivalent single-diode circuit model are considered at four different temperature values of $25 \degree C$, $45 \degree C$, $65 \degree C$, and $85 \degree C$ for 100 days duration. The parameters are estimated by the known values of $V_{oc}$, $J_{sc}$, $V_{mp}$, and $J_{mp}$ derived from the SCAPS-1D simulation environment.

The trends of changes in $R_{s}$ values at different temperatures through time are illustrated in Fig. 3. It should be noted that the lower value of $R_{s}$ indicates a better performance of the solar cell, where $R_{s}$ = 0 is the ideal case. Therefore, the higher values of $R_{s}$ at higher temperatures in Fig. 3 are consistent with the lower performance of the solar cell at higher temperatures. As shown in Fig. 3, $R_{s}$ has an almost uniform and small increment at the standard temperature $T = 25 \degree C$ (from 0.75 $\Omega$/cm² at 0 h to 0.95 $\Omega$/cm² at 2400 h) which indicates a normal aging process.

However, the $R_{s}$ trajectories at the other temperatures have non-uniform increments through time. For example, $R_{s}$ trajectories have breaking points around $t = 1760$ h for $T = 45 \degree C$, around $t = 1340$ h for


Table 1. The $J - V$ characteristic values for $T = 25{\degree}C$ and $T = 85{\degree}C$ at different time instants.

| Time (h) | $V_{oc}$ (V) | $J_{sc}$ (mA/cm$^2$) | FF (%) | PCE (%) | $V_{oc}$ (V) | $J_{sc}$ (mA/cm$^2$) | FF (%) | PCE (%) |
|----------|---------------|----------------------|--------|---------|---------------|----------------------|--------|---------|
| 0        | 0.439         | 17.77                | 67.8   | 5.30    | 0.389         | 15.76                | 59.9   | 3.67    |
| 750      | 0.437         | 17.34                | 65.9   | 5.00    | 0.384         | 14.70                | 57.3   | 3.24    |
| 1500     | 0.435         | 16.94                | 64.2   | 4.74    | 0.364         | 9.07                 | 49.0   | 1.78    |
| 2400     | 0.431         | 16.09                | 61.1   | 4.25    | 0.304         | 3.01                 | 40.6   | 0.35    |


**Fig. 3.** The plots of the series resistance variations over time at different temperatures.

$T = 65{\degree}C$ and around $t = 1170$ h for $T = 85{\degree}C$. After the breaking points, sudden slope changes occur which indicate the early aging process and early degradation of the solar cell. Also, the rate of increment for $R_s$ is increased at higher temperatures. At $T = 45{\degree}C$, $R_s$ reaches 3.18 $\Omega$/cm$^2$ at 2400 h from 1.05 $\Omega$/cm$^2$ at 1760 h, while $R_s$ is increased from 1.2 $\Omega$/cm$^2$ at 1170 to 4.1 $\Omega$/cm$^2$ at 2400 h for $T = 85{\degree}C$.

These results confirm that the aging process is enhanced at higher temperatures. The aging process is continued at almost the same rate after the breaking point and early aging occurs after this time instant. As a result, it is essential to detect the early aging phenomenon before permanent damage to the cell.

The trajectories of the $R_s$ over time at different temperatures are shown in **Fig. 4.** Unlike $R_s$, the higher value of $R_s$ represents a better performance of the solar cell and for the ideal case, we have $R_s = 0$. It can be observed from **Fig. 4** that $R_s$ values decrease in the course of time at all temperature values. The results verify the aging process in the PSC and the fact that the cell performance decreases at a higher temperature. However, all the trajectories are decreased with an almost uniform rate and without any sharp variation. For example, the differences between the left and right endpoints for this parameter at $T = 25{\degree}C$ and $T = 85{\degree}C$ are about 60.8 $\Omega$/cm$^2$ and 59 $\Omega$/cm$^2$, respectively. Indeed, the error in $R_s$ from its nominal value has the least impact on the $J - V$ curve variations with respect to the other parameters. Hence, this parameter is not an acceptable indication of the early aging process in the T-PSC.

The trends of changes in the photocurrent variable at different temperatures are illustrated in **Fig. 5.** Obviously, higher values of $J_{ph}$ are desirable for a solar cell. As the temperature is increased, the $J_{ph}$ value decreases. Since the value of this variable is very close to the $J_{sc}$ value at any environmental condition, its variation is a reliable index for recognizing the aging process in the PSCs. On the other hand, the trajectories in **Fig. 5** have a desirable consistency with $R_s$ trajectories in **Fig. 3.** In other words, similar patterns and braking points can be observed for $J_{ph}$ and $R_s$. The only difference is that $J_{ph}$ trajectories have descent slopes while $R_s$ trajectories have ascent slopes. For instance, the normalized rates of the change for $R_s$ and $J_{ph}$ at $T = 45{\degree}C$ from the breaking point are 0.67 and $-0.61$, respectively. A similar analysis at $T = 65{\degree}C$ leads to the values 0.65 and $-0.62$. Considering the magnitudes, the rates of change of $R_s$ and $J_{ph}$ are very close to each other for all the environmental conditions. The only difference is related to the different slope signs in these two variables. These results justify the reliability of the $R_s$ variable to be considered for early aging fault detection in the T-PSCs.

The diode saturation current density $J_0$ is another parameter in the single-diode circuit model. The lower value of $J_0$ represents a solar cell with higher performance. The trends of variations in this parameter considering different temperature values are shown in **Fig. 6.** Again, similar breaking points at different temperatures can be observed in this figure and the trajectories are strictly increasing. Thus, early aging is observable from the $J_0$ trajectories at higher temperatures. Although $J_0$ has more impact on the $J - V$ curve with respect to $R_s$, it has less effect...
Monitoring the variations on the slopes of the $R_i$ trajectories can be considered a reliable technique for early aging detection in T-PSCs. On the other hand, aging is a gradual process that occurs over time and the instantaneous slope variation is not a reasonable indicator. The sudden change in the slope value in $R_i$ variable may be encountered because of some other faults such as temporary partial shading or hotspot conditions which are not related to the early aging process.

Hence, the linear regression analysis is utilized for early aging fault detection in the T-PSCs. By this statistical method, a linear function $f(t) = mt + b$ is fitted to the estimated $R_i$ values from the beginning up to the last data point. The unknown variables $m$ (the slope of the fitted line) and $b$ (the vertical intercept) are estimated by the ordinary least square technique. Here, $m$ represents the gradient of the fitted linear function considering all the data points and the variation of this variable is a reasonable index for investigating the aging process in T-PSCs. Thus, early aging detection can be described as follows. At a time zero, the T-PSC variables $V_{oc}$, $J_{sc}$, $V_{mp}$, and $J_{mp}$ are measured and the $R_i$ value is estimated from (19) and the convex method in Section 2. This process is repeated after a certain amount of time and the same calculations are implemented to generate the second and third estimations of the series resistance. Then, the linear regression analysis is applied to the first three data points to obtain the corresponding $m$ variable. By measuring the $V_{oc}$, $J_{sc}$, $V_{mp}$, and $J_{mp}$ variables at the current time and estimating the corresponding $R_i$ value, a new regression analysis is applied. Hence, the gradient variable is achieved for four sets of data. A similar procedure can be applied to obtain the fitted line slope variable in real-time. Hence, the early aging process can be determined from the trend of variations in $m$ variable from zero up to the current time.

The regression analysis on the estimated series resistance data points over time and at different temperatures values are shown in Fig. 8(a-d). Also, the quantitative values are reported in Table 2 for better insight into the aging process. It can be observed from Fig. 8a that the gradient variable $m$ does not change, significantly at $T = 25^\circ$C. In fact, it starts from $m = 99.1 \times 10^{-6}$ for three data points and it changes to $m = 67.2 \times 10^{-6}$ for four data points. This reduction in $m$ is related to the performance of the T-PSC and the operation condition of the device at $t = 68$ h corresponding to the second data point ($n = 2$). The reduction of $m$ is continued until the fifth data points ($n = 5$), where the lowest value $m = 59.2 \times 10^{-6}$ is achieved around $t = 1000$ h. After this time the gradient $m$ from the regression analysis is started to increase and it reaches $m = 74.8 \times 10^{-6}$ after 2400 h. By comparing this value with the gradient value at $t = 1000$ h, it is revealed that $m$ has a $24.6\%$ increment. This result verifies the normal aging process in the device at the standard temperature value of $T = 25^\circ$C.

A similar pattern can be observed for the gradient value $m$ at other temperatures (Fig. 8(b-d)), where the minimum value of $m$ is achieved at $T \geq 5$ corresponding to $t = 1000$ h. After this time the gradients $m$ are strictly increasing to the higher values. However, the rate of increments is much higher than the standard temperature value $T = 25^\circ$C. For example, $m = 11.3 \times 10^{-5}$ is the lowest value at $t = 1000$ h and $m = 72.6 \times 10^{-5}$ is the highest value at $t = 2400$ h for $T = 45^\circ$C. In other words, the rate of increment for the gradient from the regression analysis is equal to $54.2\%$, which is much larger than $26.4\%$ at the standard condition. The rates of increments in $m$ at $T = 65^\circ$C and $T = 85^\circ$C from their lowest values at $t = 1000$ h to their largest values at $t = 2400$ h are $481.6\%$ and $691.6\%$, respectively. Hence, at high temperatures, there is a higher possibility of early aging and degradation in the performance of the T-PSC. As a result, it is important to detect this undesirable condition in advance, to protect the T-PSC from any destruction and permanent damage.

For early aging fault detection, a mathematical index is considered as:

$$\frac{m_n - m_{min}}{m_{min}} \geq 1$$

Fig. 6. The plots of the diode saturation current variations over time at different temperatures.

Fig. 7. The plots of the diode ideality factor variations over time at different temperatures.

on the $J-V$ characteristic compared with $R_i$. Therefore, $J_0$ cannot be considered a better index for early aging fault detection.

The effect of temperature on the diode ideality factor in the early aging process in the T-PSC is illustrated in Fig. 7. The ideality factor $a = 1$ represents a solar cell with good performance and the cell functioning is decreased by the increment of this value from one. Similar to the $R_i$, this value is monotonically increased during the time which represents the aging process in the device. Also, the rates of ascending increases at certain times for the higher temperatures. In addition, this variable has a high impact on the $J-V$ characteristic of the solar cell. However, the diode ideality factor trajectories for $T = 65^\circ$C and $T = 85^\circ$C are very close and it is difficult to distinguish them from each other as indicated in Fig. 7. As a result, this value cannot be considered an index for early aging detection in the T-PSC at different temperatures.

As discussed, $R_i$ is a desirable variable for early aging detection in T-PSCs. Because this parameter has a significant effect on the $J-V$ characteristic and its variation from its nominal value can be considered as an indication of the fault in the device. Also, the breaking points and the trends of changes are distinguishable at different temperatures as shown in Fig. 3. A mathematical analysis is provided in the supplementary information to show the impact of error in each parameter from the nominal value on the J-V curve.
Table 2. The variations of m from regression analysis at different temperatures and time instants.

| Data points No. | Time (h) | 25°C | 45°C | 65°C | 85°C |
|-----------------|----------|------|------|------|------|
| n = 3           | 400      | 0.0000991 | 0.000161 | 0.000202 | 0.000210 |
| n = 4           | 730      | 0.0000672 | 0.000124 | 0.000163 | 0.000164 |
| n = 5           | 1000     | 0.0000592 | 0.000113 | 0.000152 | 0.000154 |
| n = 6           | 1035     | 0.0000608 | 0.000119 | 0.000163 | 0.000164 |
| n = 7           | 1170     | 0.0000619 | 0.000122 | 0.000166 | 0.000178 |
| n = 8           | 1340     | 0.0000619 | 0.000127 | 0.000167 | 0.000269 |
| n = 9           | 1515     | 0.0000614 | 0.000131 | 0.000285 | 0.000433 |
| n = 10          | 1760     | 0.0000608 | 0.000132 | 0.000420 | 0.000584 |
| n = 11          | 1805     | 0.0000630 | 0.000220 | 0.000539 | 0.000734 |
| n = 12          | 1950     | 0.0000650 | 0.000362 | 0.000639 | 0.000835 |
| n = 13          | 2150     | 0.0000701 | 0.000504 | 0.000744 | 0.001042 |
| n = 14          | 2400     | 0.0000748 | 0.000726 | 0.000884 | 0.001219 |

where $m_i$ is the current value of m from the regression analysis for all the data points from the beginning up to the last estimated $R_s$ value and $m_{\text{min}}$ is the minimum $m$ that has been achieved up to the current $m$. In other words, at the time that the magnitude of the gradient $m$ is equal to or larger than two times the minimum $m$ is an acceptable index to detect early aging in the T-PSC. According to the mathematical index (20) and the data points in Table 2, the fault detection time for $T = 45 ^\circ C$, $T = 65 ^\circ C$ and $T = 85 ^\circ C$ are 1950 h, 1760 h, and 1515 h, respectively. It can be seen that the fault detection time is decreased by the temperature increment. Obviously, no fault is detected at $T = 25 ^\circ C$ because the highest value of $\frac{m_{\text{max}}-m_{\text{min}}}{m_{\text{min}}} = 0.26 < 1$ is achieved at 2400 h with $m_{\text{max}} = 74.8 \times 10^{-6}$. These results verify the normal aging of the device at the standard temperature. Hence, the proposed approach can be utilized to distinguish between the normal and early aging processes while the fault can be detected at the proper time in the case of faulty conditions. There are some important points considering the fault detection index (20) which are expressed as remarks in the following.

Remark 1. The $m_{\text{min}}$ value is not achieved from the first three data points, necessarily. For example, in this simulation, the $m_{\text{min}}$ value is achieved from the fifth data point at $t = 1000$ h at all temperatures. The reasons for this condition can be related to the performance of the PSC and the environmental condition.

Remark 2. For a more conservative fault detection strategy, one can consider a value smaller than one on the right side of inequality (20). In this way, the early aging can be detected faster and the solar cell can be protected, significantly. For example, with the assumption of $\frac{m_{\text{max}}-m_{\text{min}}}{m_{\text{min}}} \geq 0.7$, the fault detection times are decreased to 1805 h, 1515 h, 1340 h for $T = 45 ^\circ C$, $T = 65 ^\circ C$ and $T = 85 ^\circ C$, respectively. According to $T = 25 ^\circ C$, where the normal aging condition is existed (with $\frac{m_{\text{max}}-m_{\text{min}}}{m_{\text{min}}} = 0.264$), the value 0.3 can be considered as the lowest reasonable and the most conservative value on the right side of inequality (20).

Remark 3. Another approach for detection of early aging in a more conservative and reasonable time is to increase the number of $R_s$ estimations for a certain amount of time. For instance, if $0 \leq \frac{m_{\text{max}}-m_{\text{min}}}{m_{\text{min}}} \leq 0.1$, the next sampling time ($\Delta t$) can be considered as the relatively large value of time. For higher values of $\frac{m_{\text{max}}-m_{\text{min}}}{m_{\text{min}}}$, the smaller values of $\Delta t$ can be considered. Hence, $\Delta t$ can be a time-varying parameter that is adjusted according to the $\frac{m_{\text{max}}-m_{\text{min}}}{m_{\text{min}}}$ index value.

Remark 4. The temporary and undesirable high temperature is common in PV applications. The main reasons for high temperatures are solar irradiation, environmental temperature, electrical load, and partial shading conditions. Although the PV cells do not encounter continuous high temperatures during the day, the early aging procedure can still arise. Moreover, the proposed early aging detection algorithm is independent of both time and the stress factor and its main purpose are to recognize the early aging condition and distinguish it from the normal aging conditions. Obviously, the higher average temperatures during the day result in faster early aging detection which shows the effectiveness of the proposed algorithm.

For a better insight into the proposed early aging fault detection algorithm, a flowchart is given in Fig. 9. A brief discussion on the flowchart is provided in the following. The algorithm is started from the initial time $t = t_0$. In fact, $t_0$ is the time that we want to apply the fault detection algorithm where $t_0 = 0$ is a viable choice. The counter
Fig. 9. The flowchart aimed at diagnosing early aging in a T-PSC.
\( i \) is introduced with the initial value \( i = 1 \). The four key parameters \( V_{oc}, J_{SC}, V_{max}, \) and \( \Delta E \) are extracted from the \( J-V \) curve by the real measurements or computer simulation (based on subsection 2.1). The corresponding values are transferred to the parameter estimation algorithm as the inputs and the estimation of \( R_s \) is achieved as an output from the gradient-based adaptive update law (19). This procedure is repeated at three different times to obtain three data points for \( R_s \). The next sampling time is determined as \( i = i + \Delta t \) where the constant \( \Delta t \) shows the time difference between the current and the next sampling time for \( R_s \) estimation. After collecting the three estimated \( R_s \) data points, the linear least square technique is applied to find the best linear function \( m_i t + b \) which fits the points. For now, the calculated \( m_i \) value is also considered as the minimum value \( \left( m_{\text{min}} = m_i \right) \). Then, a conditional loop is defined where the inequality \( \frac{m_i}{m_{\text{max}}} \) is considered as the required condition for remaining in the loop. The procedure to find the \( i \)th series resistance estimation \( \left( R_{s,i} \right) \) and the corresponding \( m_i \) value considering all the data points is similar to the steps explained for the first three data points. The only difference is corresponding to the variable time difference \( \left( \Delta t_i \right) \) between the estimated \( R_s \) values. The value of \( \Delta t_i \) at each iteration can be adjusted considering Remark 3. There is also an additional task in the loop, in which \( m_i \) is assigned to the minimum value of \( m \) in the case that \( m_i < m_{\text{min}} \). The algorithm remains in the loop unless the inequality (20) is obtained which indicates an early aging fault in the T-PSC. In particular, for \( T = 45^\circ\text{C} \) the loop is terminated at 1950 h and for \( T = 25^\circ\text{C} \) the algorithm does not exit the loop which indicates a normal aging process in the device.

It is worth mentioning that although the values of \( V_{oc}, J_{SC}, \) and FF are changed during the aging condition, the variations of the single-diode circuit model are more reliable for early aging detection. Because for extracting the five unknown parameters both the current density and voltage variables are considered, simultaneously. Also, these five parameters represent the whole \( J-V \) curve not only a few particular points. Moreover, generating an accurate PV model can be utilized for other purposes such as monitoring, recognizing other possible faults, and maximum power point tracking.

4. Conclusion

The stability of a T-PSC is one of the main challenges of this device, which can lead to early aging of the cell and its permanent damage eventually. Among all the environmental factors involved in the early aging process of the T-PSC, the temperature is the most significant one. Here, the SCAPS-1D software is used to simulate the behavior of a T-PSC, considering excess electron and defect concentrations. By evaluating the PCE, FF, and \( J-V \) characteristics at different operating temperatures, it was shown that the rate of aging dramatically increases at higher temperatures. Also, the impact of temperature on the trends of variations of the five parameters in the equivalent single-diode circuit model at different temperatures over time was investigated. The five parameters were estimated through an accurate and convex optimization approach. It has been verified that the series resistance is the most reliable parameter for defining an index for early aging detection. Finally, the relative variation of the gradient with respect to its minimum in the linear regression analysis derived as a mathematical index for fault detection. The fault detection time for \( T = 45^\circ\text{C}, T = 65^\circ\text{C} \) and \( T = 85^\circ\text{C} \) are 1950 h, 1760 h, and 1515 h, respectively and at \( T = 25^\circ\text{C} \) there is a normal aging process. The proposed method is very precise and can detect early aging at a proper time to protect the cell from any permanent damage and increase its life cycle. It should also be noted that the proposed early aging detection method can be applied to any PV cell. The reason for choosing the popular T-PSC is related to their significant challenge of instability under thermal stress conditions.

Declarations

Author contribution statement

Hossein Amanati Manbar, Ehsan Moshksar: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Zahra Hosseini, Teymoor Ghanbari: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Mohammadali Khodapanah: Performed the experiments; Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

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