Evaluation of Mismatch Losses due to Shunts in industrial Silicon Photovoltaic Modules

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Abstract. In order to achieve higher efficiencies in photovoltaic module technology, it is important to characterize the shunts and other defects which degrade the performance of cells and modules as well as decrease their efficiency. These shunts also affect the reliability of cells and modules. It is important to understand how much fill factor and power loss is caused by the presence of shunts in the module. Shunts not only reduce the module power output, but also affect the I-V characteristics of the cell and hence the characteristics of the shunted cells are different from those of the shunt-free cells connected in the module leading to the mismatch effect. This is an interesting effect which has been systematically investigated in the present work. Moreover, the flow of increased shunt current will give rise to increased temperature in the region of shunt, which will affect the cell and hence module performance. In the present study, the distributed diode model has been extended to the module level and applied to evaluate the electrical mismatch losses and thermal mismatch losses due to shunts in industrial Silicon PV modules.

1. Introduction
Photovoltaic cells often suffer from localized shunts, which are internal short circuits causing degradation in the cell performance and overall efficiency [1, 2]. The presence of a shunted cell within a module can severely influence the efficiency and reliability of the entire module [3, 4]. Further, the reliability of Silicon-based photovoltaic cells can be limited by thermal issues occurring in regions with high localized self-heating or hot spots born from the shunts, which are often observed to induce a strong degradation of the photovoltaic cell and of the module itself leading to a drastic reduction of the module life time and even to hazardous operating conditions [5]. The reliability issues cited above can be aggravated when a PV cell operates in reverse bias condition, which might take place when one PV cell in a module is shaded and others are still generating current [5]. In this case, a significant reverse current can flow through the shaded cell and this may lead to a premature break down and permanent degradation [6, 7], because the current is observed to flow through the shunt resistance. In the presence of a low shunt resistance, breakdown often occurs at localized sites [3].
It would be interesting to understand the possible mismatch effects arising due to the presence of a shunted cell or a number of shunted cells on the PV module performance. Since the shunts can have a dramatic influence on the I-V curve of the PV cell, degrading the cell’s output power, open circuit voltage and fill factor, it is natural to expect a critical influence on the performance of PV module as well.
The aim of the present work is to present a systematic study of the effect of an ohmic shunt on the performance of an industrial Silicon photovoltaic module. Distributed diode model [8-11] developed based on experimentally measured parameters has been extended to simulate the PV module performance. A series connected module with 36 cells has been considered in the present work.

2. Approach and methodology
Since the shunts essentially affect the I-V characteristics of the solar cells, it is expected that they would cause mismatch losses in the PV module performance. The quantum of the mismatch losses due to shunts in a PV module has not been studied thoroughly as yet. Hence an approach has been devised to study the mismatch losses due to shunts. The focus will be on the part of the losses which could be possibly caused by the fact that the particular cell or cells which due to shunting operates at a lesser voltage compared to the other cells in the series connection. To take into account the fact that generally the modules are series connected and to simplify the approach, only the series connection of the module has been considered presently.

Photovoltaic modules have a large area and hence, there are a lot of parameters that possess spatial inhomogeneities like material defects, illumination intensity etc. Distributed diode model offers freedom in employing the inhomogeneities in one or all parameters and estimating the output from the PV module. Many effects can be studied and their influence on module performance can be analyzed. Distributed diode model developed in the present work has been exploited to find the shunt currents in the shunted and non-shunted regions of the shunted cell or cells connected in the PV module. Presently, an improved 3-D model has been utilized in order to find the temperature rise. Since the most important factor which is principally affected by temperature is the reverse saturation current, its value has been found by the 3-D model and the new value is used to find the module I-V after temperature rise due to shunts.

In the distributed diode model, each PV cell is divided into smaller elementary areas and the model has been utilized to study thermal mismatch losses by computing the shunt currents flowing for various cases of shunting at the shunt locations.

The presence of shunts causes increase in leakage current. Through the simulation of distributed diode model, the currents flowing through each shunt resistance in the elementary area can be evaluated. These shunt currents flowing in the shunt locations generates heat, which further causes an increase in temperature in that region. This temperature rise can be estimated by using an electrical equivalent circuit of thermal model, which has been explained in section 3.

3. Model

3.1. Distributed Diode Model
In the distributed diode model [10, 11], as shown in figure 1, each PV cell is divided into smaller elementary areas and each elementary area is modelled by Shockley’s one diode model. These smaller areas are assumed to be homogeneous and are replaced by lumped single diode model circuits. The smaller area circuits are interconnected to make the entire model of solar cell. Each cell in a module is connected in series, which is interconnected with bus bar resistors. In this way, the homogeneity can be localized to small regions and the effects of individual region on the entire module performance can be analyzed.

For simulation of a PV cell and module using distributed diode model, each cell area is divided into 1421 elements. The parameters of the division are calculated according to the dimensions of the elementary area of the distributed diode model provided in the table 1. The simulation was carried out using PSpice circuit simulator.

3.2. 3D Thermal Model

3.2.1. Analogy between electrical and thermal quantities. The analogy between electrical and thermal quantities, from table 2 is utilized to build an electrical R-C network model that simulates the thermal
response. The heat generated at the shunt locations is used in this model to find out the temperature rise at that location. The quantities are explained in table 3.

3.2.2. Electrical Equivalence of thermal model. Any material, during the heat transfer phenomenon, absorbs a part of the heat and the rest of the heat gets diffused through the material and transmits according to Fourier’s law. If the material is located in the atmosphere, part of the energy is lost through convection to the surrounding air. The whole process can be modelled by a RC-network model using the analogy between electrical and thermal quantities. The thermal resistance and heat capacity of the material in figure 2 are transformed into electrical resistance and capacitance accordingly as in figure 3. The electrical parameters corresponding to the thermal quantities are given in table 4.

![Figure 1. Distributed diode model of the solar cell showing only 3x3 elementary areas and wherein each elementary area is modelled by Shockley’s one diode model.](image)

### Table 1. Simulation parameters.

| Parameters                   | Value                |
|------------------------------|----------------------|
| Number of busbars            | 1                    |
| Number of fingers            | 14                   |
| Cell length                  | 6.2 cm               |
| Cell breadth                 | 3.7 cm               |
| Number of elementary areas   | 1421                 |
| Number of rows               | 29                   |
| Number of columns            | 49                   |
| Photo-generated current      | 4.715E-04 A          |
| Reverse saturation current   | 7.83E-10 A           |
| Ideality factor              | 1.7                  |
| Shunt resistance (shunt-free area) | 7.815E05Ω/sq.    |
| Sheet resistance             | 40 Ω/sq.             |

### Table 2. Electrical and thermal quantities analogy.

| Equations                       | Analogy          |
|---------------------------------|------------------|
| \( I = \frac{\Delta V}{R_e} \); \( q = \frac{\Delta T}{R_t} \) | \( V \leftrightarrow T \) |
| \( R_t = \frac{l}{kA} \)            | \( R_e \leftrightarrow R_t \) |
| \( I = \frac{dV}{dt} \); \( q = m c_p \frac{dT}{dt} \) | \( C \leftrightarrow m c_p \) |

The heat that is conducted through the layers can be seen as the current flowing through the resistors. During this process the layers get heated up and some heat is stored in the layers. This storing of heat is similar to storage of charge by a capacitor when a current flows through it. The temperature rise at
any location can be found from the electrical equivalence of thermal model as the voltage at that point. Steady state response is taken into consideration in the methodology adopted for solution.

3.2.3. Effect of Temperature. Rise in temperature causes change in the saturation current of the semiconductor. Even if the temperature rise at a single elementary area is small, the effect of change in saturation current, which result in considerable drop in performance, becomes significant on considering the large number of elementary areas involved in the case of an extended shunt. The saturation current is affected by many parameters as shown in equation (1), of which the intrinsic carrier concentration is the most significant. The intrinsic carrier concentration is dependent on band gap and the temperature, as seen in equation (2). Their concentration increases as the band gap reduces, which is caused by the temperature rise. Equation (3) reveals the critical influence of temperature on the saturation current.

\[
I_0 = qA \frac{Dn_i^2}{LND} 
\]

\[
n_i^2 = 4 \left( \frac{2 \pi k T^3}{h^2} \right) (m_e^* m_h^*)^{3/2} \exp \left( \frac{-E_{GO}}{kT} \right)
\]

\[
I_0 = B' T^3 \exp \left( \frac{-E_{GO}}{kT} \right)
\]

where \(I_0\) is the reverse saturation current, \(q\) is the electron charge, \(A\) is area of the elementary area, \(D\) is the diffusivity of minority carriers, \(N_D\) is doping, \(k\) is Boltzmann constant, \(h\) is Planck’s constant, \(m_e^*\) is the effective mass of electron, \(m_h^*\) is the effective mass of hole, \(n_i\) is the intrinsic carrier concentration, \(L\) is the diffusion length, \(T\) is temperature, \(B'\) is a constant, and \(E_{GO}\) is band gap linearly extrapolated to absolute zero.

3.2.4. Material Specifications of the PV Module. The simulation model has been formulated based on a 10W PV module whose parameters are summarized in table 1. Material specifications of the PV module modelled in the study are detailed in table 5. Accuracy in determination of temperature rise has been improved by 3D thermal model. Distributed diode model has been exploited thereafter to determine thermal mismatch losses due to shunt currents flowing in some defined regions in the cells connected in series in the module. Thermal mismatch has effect on power, fill factor, module open circuit voltage, and operating point of the module. The last mentioned effect is felt on the loss in voltage and current at the MPP (Maximum Power Point).
Each of these has been studied and results are shown in bar charts for more clarity and for comparison. Both thermal and electrical mismatch effects have been combined in order to show explicitly the effect of temperature rise due to the shunt currents.

**Table 3.** Description of quantities.

| Symbol | Quantity          |
|--------|------------------|
| $I$    | Current          |
| $V$    | Voltage          |
| $R_e$  | Electrical resistance |
| $C$    | Capacitance      |
| $q$    | Heat energy      |
| $R_t$  | Thermal resistance |
| $l$    | Thickness of layer |
| $k$    | Thermal conductivity |
| $A$    | Area of the elementary area |
| $m$    | Mass of the elementary area |
| $C_p$  | Specific heat capacity of material |

**Table 4.** RC network elements corresponding to thermal quantities.

| Thermal Resistance | Electrical Resistance |
|--------------------|-----------------------|
| Top convection     | RF_conv               |
| Glass              | R_glass               |
| Front EVA          | RF_eva                |
| Silicon            | R_Si                  |
| Back EVA           | RB_eva                |
| Tedlar             | R_Tedlar              |
| Bottom convection  | RB_conv               |

**Table 5.** PV module material specifications. [12]

| Parameter  | Thickness (m) | Thermal Conductivity (W/m-K) | Specific Heat (J/kg-K) | Density (kg/m³) |
|------------|---------------|------------------------------|------------------------|-----------------|
| Glass      | 3.20E-03      | 1.8                          | 5.00E+02               | 3.00E+03        |
| Front EVA  | 4.00E-04      | 0.35                         | 2.09E+03               | 9.60E+02        |
| Silicon    | 2.25E-04      | 148                          | 6.77E+02               | 2.33E+03        |
| Back EVA   | 4.00E-04      | 0.35                         | 2.09E+03               | 9.60E+02        |
| Tedlar     | 1.25E-04      | 0.2                          | 1250                   | 1200            |

4. Results and discussion

The intensity of illumination falling on the different solar cells connected in the module determines primarily the amount of current generated in each cell. Hence it becomes an important parameter to be considered in the mismatch situation. However, the present study assumes that all cells in the module are uniformly illuminated.

4.1. Comparison of performance of shunted cell in the module and non-shunted cell

The most important parameter determining the quantum of the effect due to shunting is the shunt magnitude or to put it more simply the value of the shunt resistance offered by the cell. The value of the shunt resistance of the cell is in turn determined primarily by the shunt resistance of the shunted area of the cell and area of the shunted region. To have a realistic picture of the shunting severity and the resulting mismatch, an overall shunt magnitude of 10 ohm has been chosen for the shunted region, which value has been found acceptable from the published literature.
From the Lock-in Infrared Thermography (LIT) images, it has been observed that the edge shunt is normally occurring in many of the cells connected in the module. The edge shunt has been simulated by taking an area of 90 nodes, whereas the total cell area is represented by 1421 nodes as shown in Table 1. An overall shunt magnitude of 10 ohm has been simulated over the shunted area. The severity of the shunting due to this shunted area can be gauged from the graph shown in figure 4, which shows the power curve of the shunted and non-shunted cell connected in series in the module. The curve has been plotted with respect to the module voltage instead of corresponding cell voltages for the purpose of comparison.

The shunted cell power curve goes even into the third quadrant and becomes negative for some voltage range which means effectively it becomes a power dissipater rather than a power generator. The power generated by the shunted cell in each situation has been estimated from the cell current and the corresponding cell voltage. To have a common reference for comparison, the module voltage in the situation which has only one shunted cell has been taken on x-axis. Due to mismatch, the shunted cell has been forced into reverse bias by the remaining non-shunted cells operating at a forward voltage, for module voltage ranging from 0V (short circuit condition) up to 15 V. This means that if the operating point of the module shifts to the region corresponding to the said voltage range, the effect of mismatch losses would impact the module output power adversely. For the particular case of module shown in the figure 4, the shunted cell was dissipating a power of 6.15 mW at near short circuit or no load conditions.

![Figure 4. Variation of shunted and shunt-free cell power with respect to the module voltage.](image)

4.2. Mismatch losses when all cells are equally illuminated

The module, normally a series connection of 36 PV cells, is simulated using distributed diode model where each cell is an interconnected network of one diode model circuits. The shunt currents are used to find the heat generated followed by investigation of rise in temperature at the shunt location by the simulation of electrical equivalent thermal model which utilizes the analogy between electrical and thermal quantities. The change in saturation current due to temperature rise is calculated. Modified saturation current is used at the shunt locations to simulate the module performance again using the distributed diode model. The performance of shunted module before and after the temperature rise is compared with that of the non-shunted module under study. The comparison between the electrical and thermal degradation effects for different spatial locations of shunting has been studied.

4.2.1. Effect of Mismatch on Module Output Power. figure 5 shows the effect of thermal mismatch on module relative power loss as a percentage of module power when all cells are non-shunted. If only one cell is shunted by a magnitude of 10 ohms, the mismatch loss in power will be a small fraction of total power. However, as number of shunted cells increases, the effect becomes significant.

4.2.2. Effect of Mismatch on Module Fill Factor. The loss in Fill Factor (FF) is depicted in figure 6. Comparing the effects on power and Fill Factor leads to the following conclusion that, the FF is degraded more than power, but because of combination of these two effects there is a notable degradation due to electrical and thermal mismatch in the module performance.
4.2.3. Effect of Mismatch on Module Open Circuit Voltage. An interesting insight has been gained from the study that, even though only 10 ohm magnitude shunts have been considered, there is a notable change in the open circuit voltage of the module due to mismatch effect. Figure 7 shows the variation of loss in module open circuit voltage (Voc) before and after temperature rise due to shunts for different number of shunted cells. The loss in Voc is increased considerably due to thermal effects. The increase in temperature clearly degrades Voc rather than Isc, the short circuit current, possibly due to the change in band gap of semiconductor with temperature.

![Figure 5. Variation of relative power loss before and after temperature rise due to shunts for different number of shunted cells.](image1)

![Figure 6. Variation of loss in fill factor before and after temperature rise due to shunts for different number of shunted cells.](image2)

![Figure 7. Variation of loss in module open circuit voltage before and after temperature rise due to shunts for different number of shunted cells.](image3)

5. Conclusions

A detailed study on the electrical and thermal mismatch effects of shunts on the performance of PV modules, have been conducted using the distributed diode model in combination with the 3-D thermal model. The investigation has yielded very interesting results, on how the shunts may cause performance loss due to mismatch and presented a novel approach to evaluate the actual power loss and fill factor loss as well as loss in open circuit voltage caused by the shunts and its temperature effects. The temperature rise due to shunt currents has been studied with a 3D thermal model so that the lateral heat flow also is considered in the model.

6. References

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