4. A lot of factors affect the variation of the maximum power (or, equivalently, the efficiency) with irradiance and temperature. The parameter γ is defined as the relative decrease in module efficiency per degree centigrade of cell temperature increase

$$\eta(T_{\text{cell}}, G) = \eta(\text{STC}) \times [1 - \gamma(T_{\text{cell}} - 25^{\circ}\text{C})]$$

Usual γ values are near 0.5% per degree centrigrade.

7.9.2 Fabrication Spread and Mismatch Losses

So-called mismatch losses arise when cells with different $I-V$ characteristics are interconnected because of the fewer degrees of freedom left to bias the devices, so that the array output is less than the sum of the powers that the individual cells could deliver. The differences come from the unavoidable fabrication spread or from nonuniform irradiance or working temperature within the array.

To minimize mismatch losses, finished cells are measured and sorted in the factory. For series connection, the important parameter is the current at the maximum power point (mpp). It is the common practice to measure the current before encapsulation at a fixed voltage close to the mpp and to classify the cells accordingly, though other classification criteria are possible [134]. Within each class all devices present similar currents within the specified tolerance that ensures that, when connected in series to form the module, the mismatch loss will be below the desired limit [135]. Depending on the class being processed, the power rating of the resulting module will vary and this explains why manufacturers offer different module families though they are built in exactly the same way.

7.9.3 Local Shading and Hot Spot Formation

Because of local shading or failure, one or several solar cells can present a much smaller short-circuit current than the rest of devices in the series string. If the defected cells are forced to pass a current higher than their generation capabilities, they become reverse-biased, even enter the breakdown regime, and sink power instead of sourcing it.

Figure 7.20 illustrates this behavior for an 18-cell string with one cell shaded so that its short-circuit current is half that of the remaining devices. String short-circuit is marked with a horizontal line, showing that in this condition the shaded cell is strongly reverse-biased and dissipates the power produced by the unshaded cells. This effect of course severely degrades the efficiency of the module, but more important is the fact that it can get damaged.

Avalanche breakdown is characterized by a nonuniform distribution of current across the junction, breakdown occurring preferentially at localized regions, possibly correlated to damage during processing. Intense local heating can produce very high temperatures (a hot spot). If a temperature of around 150°C is reached, the lamination material becomes degraded and the module irreversibly deteriorated [136, 137]. Because of the localized nature of the process solar cells show large scattering in their reverse characteristics so that the module behavior under partial shading is not accurately predictable.