**Problem 7.1** Download Panasonic Evervolt 390H panel datasheet from the manufacturer’s website or from this book’s online repository.:

1. The main electrical parameters under Standard Test Conditions (STC) are:

* *V*OC = 48.6 V
* *I*SC = 10.19 A
* *P*max = 390 W
* Module efficiency: 21.1%
* Temperature coefficients:
  + Power: *γ*Pmax = -0.26 %/°C
  + Voltage: *β*Voc =  -0.24%/°C
  + Current: *α*Isc = 0.04%/°C

1. The module uses n-type half-cut heterojunction Si cells. This implies that the module is divided in two cell sub-matrices in parallel: top and bottom, *N*P = 2. This is corroborated visually by the usage of split junction boxes at the center of the module.

The number of cells in series is not stated in this datasheet, although it is a common practice to do so. Thus, we need to investigate a bit harder than usual to find out *N*S:

* Looking at the picture of the module in the datasheet, one can notice 11 different half cells per string in each module half. Since the module is 6-strings wide, there are *N*S = 11 × 6 = 66 cells in series (the 66 cells at the top are in parallel with the 66 cells at the bottom).
* The module voltage has to be approximately similar to the voltage of a single solar cell times *N*S. Since the module uses heterojunction (HJT) solar cells, *V*OC is a bit larger than in mainstream p-type PERC c-Si cells, in the range of 0.74-0.75 V at STC. Therefore,

1. Each split junction box includes a bypass diode that protects one string block at the top sub-matrix and another one in parallel at the bottom (see Fig. 7.2 and Fig. 7.17-right). There is a total of 3 bypass diodes, 3 junction boxes and 6 string blocks.
2. The resulting electrical layout is sketched in the next figure:



**Problem 7.2** A PV module measures 1 m × 2.01 m and it is composed of 144 half-cut cells, arranged as two sub-matrices in parallel, each consisting of 72 cells in series. The module technology is known to achieve a typical CTM power ratio around 0.98. If each half-cut cell has parameters *V*OC,cell = 685 mV, *I*SC,cell = 5.06 A and *FF*cell = 80% at STC, use simple expressions to estimate:

1. At STC:

*V*OC,module ≃ *V*OC,cell × *N*S = 0.685 V × 72 = 49.3 V

*I*SC,module ≃ *I*SC,cell × *N*P = 5.06 A × 2 = 10.12 A

1. Using Eq. (7.13):

*P*max,STC = (*P*max,STC,cell  × *N*S × *N*P) × *CTM*= 2.773 × 72 × 2 × 0.98 = 391 W

where:

*P*max,STC,cell  = *V*OC,cell × *I*SC,cell × *FF*cell = 0.685 × 5.06 × 0.8 = 2.773 W

1. The resulting electrical conversion efficiency of the module is:

*η* = *P*max,STC[W] / (module area[m2] × 1000 [W·m-2]) = 391 / (1×2.01×1000) = 19.5%

**Problem 7.3** We consider the I-V parameters given in Table 7. 1 for the LG345N1W-A5 PV module:

1. In Eqs. (7.23) and (7.24), we will use STC as starting conditions and NMOT as target conditions. Module temperature at NMOT conditions is NMOT, provided the manufacturer (table 7.1).

|  |  |  |
| --- | --- | --- |
| Parameter | Starting conditions (STC) | Target conditions (NMOT) |
| Irradiance (W/m2) | 1000 | 800 |
| Module temperature (°C) | 25 | 42 |

*I*mp is translated using Eq. (7.23):

where NMOT = 42 °C, and according to the datasheet.

*V*mp is translated using Eq. (7.24). It uses RS, which is not provided by the manufacturer, so we can estimate it using Eq. 7.17:

where all the I-V parameters are those given in the datasheet at STC, *N*S = 60, *V*T= 0.026 = *k·T*c,STC/*q*, with *T*c,STC = 298.15 K. It is safe to assume *n* = 1 for c-Si modules.

where *a* is a correction factor around 0.06, , the I-V parameters at STC are those given in the datasheet and has just been obtained in the previous step.

Finally, maximum power point is calculated as *P*max,NMOT = *V*mp,NMOT × Imp,NMOT = 262 W

1. Using Eq. (7.25):
2. The error of both estimations compared to the NMOT value provided by the manufacturer:

|  |  |  |
| --- | --- | --- |
| Manufacturer’s value for *P*max,NMOT | Independent translation of *V*mp,NMOT and Imp,NMOT | Direct translation of *P*max |
| 259 W | 262 W | 259 W |
| Error | 1% | 0% |

**Problem 7.4** We estimate the single-diode model parameters for the LG345N1W-A5 module at STC following the equations shown in Box 7.2:

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Value** | **Methodology** |
| n | 1 | Assumption for c-Si module |
| RS (Ω) | 0.21 | Eq. (7.17): I-V parameters at STC in Table 7.1; NS = 60; *V*T = 0.026 V |
| RP (Ω) | 155 | Eq. (7.18) |
| IL (A) | 10.58 | Eq. (7.20) |
| I0 (A) | 2.55·10-11 | Eq. (7.22) |

Then, we use an iterative process to find the maximum power point (*I*mp,STC and *V*mp,STC).

First, estimate *I*SC:

* Define *V* = 0;
* use Eq. (7.6) with the single-diode model parameters just obtained and a starting value for *Iguess* = *I*L to provide an initial estimation for *I*= f(*I*guess,*V*):
* use this initial estimation again in Eq. (7.6) to find a better approximation to *I*:

Since the error *I*– f(*I*guess,*V*) is lower than 1% of the estimated *I*, we accept this value as *I*SC.

Then, estimate *V*OC to check the validity of the model parameters:

* Define *I*= 0;
* you could use an initial guess for *V* ≃ *N*S · 0.7 = 42 V in Eq. (7.6):
* and iterate (trial and error) until *I* ≃ 0;
* a value of *V* = *V*OC = 41.2 yields *I*∼10-11 A, which matches the value provided by the manufacturer’s datasheet.

Finally, find a range of values around the knee of the I-V curve to catch the maximum power point (*V*mp, *I*mp):

* define a range of values of *V* around 0.8 · *V*OC in small steps (e.g. 0.5% of *V*OC):
* for each *V* value, use Eq. (7.6) with *I* = *I*SC to provide an initial estimation for *I*= f(*I*guess,*V*);
* then use this initial estimation again in Eq. (7.6) to provide a better guess for *I* and repeat until the error *I*– f(*I*,*V*) is lower than 1% of the estimated *I* (two iterations are often enough).
* Take the product *P* = *V* · *I* for each pair of values to find peak power *P*max (and *V*mp, *I*mp, accordingly).
* If the maximum value has been found at the edge of the range of *V* values, define some additional values until *P* drops again.
* If the maximum value is very far from the neighboring values, add additional points in between to improve resolution.

After only two iterations we obtain a very small error that provides the maximum power point:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **V (V)** | **Iguess (A)** | **I (A)** | **Error** | **P (W)** |
|  | 31.8 | 10.27 | 10.27 | 0.0% | 327 |
|  | 32.0 | 10.26 | 10.26 | 0.0% | 328 |
|  | 32.1 | 10.25 | 10.25 | 0.0% | 329 |
|  | 32.3 | 10.23 | 10.23 | 0.0% | 331 |
|  | 32.5 | 10.22 | 10.22 | 0.0% | 332 |
|  | 32.6 | 10.20 | 10.20 | 0.0% | 333 |
|  | 32.8 | 10.18 | 10.18 | 0.0% | 334 |
| Initial guess | 33.0 | 10.16 | 10.16 | 0.0% | 335 |
|  | 33.1 | 10.14 | 10.14 | 0.0% | 336 |
|  | 33.3 | 10.12 | 10.11 | 0.0% | 337 |
|  | 33.5 | 10.09 | 10.09 | 0.0% | 337 |
|  | 33.6 | 10.06 | 10.06 | 0.0% | 338 |
|  | 33.8 | 10.03 | 10.02 | 0.0% | 339 |
|  | 33.9 | 9.99 | 9.99 | 0.0% | 339 |
|  | 34.1 | 9.95 | 9.95 | 0.0% | 339 |
| **Pmax** | **34.3** | 9.91 | **9.90** | 0.0% | **340** |
|  | 34.4 | 9.86 | 9.86 | 0.0% | 339 |
|  | 34.6 | 9.81 | 9.80 | 0.0% | 339 |
|  | 34.8 | 9.75 | 9.75 | -0.1% | 339 |
|  | 34.9 | 9.69 | 9.68 | -0.1% | 338 |
|  | 35.1 | 9.63 | 9.61 | -0.1% | 337 |

**Problem S7.5** The solution is available as a Jupyter notebook at this book’s online repository.

**Problem 7.6**

1. Initially, we translate the single-diode model parameters obtained in Problem 7.4 to NMOT conditions (800 W/m2, NMOT cell temperature) following the approach shown in Box 7.3.

|  |  |  |  |
| --- | --- | --- | --- |
| **Conditions** | **STC** | **NMOT** |  |
| Gef(W/m2) | 1000 | 800 |
| Tc(°C) | 25 | 42 |
| Tc(K) | 298.15 | 315.15 |
| **SDM parameters** | | | **Methodology** |
| n | 1 | **1** | Considered independent of operating conditions |
| IL(A) | 10.58 | **8.51** | Eq. (7.27) |
| I0(A) | 2.55·10-11 | **3.82·10-10** | Eq. (7.29) after obtaining Eg(Tc) with Eq. (7.30). Be careful to use kB in (eV/K) as Eg is given in (eV). |
| RP(Ω) | 155 | **193** | Eq. (7.31) |
| RS(Ω) | 0.21 | **0.21** | Considered independent of operating conditions |
| **Other parameters** | | |  |
| VT(V) | 0.0257 | **0.0272** | Eq. (7.28). Here kB used in (J/K) |
| Eg(eV) | 1.121 | **1.116** | Eq. (7.30) |
| **Data** | |  | |
| αIsc(1/K) | 0.0003 |
| kB(J/K) | 1.381·10-23 |
| kB(eV/K) | 8.62·10-5 |
| q(C) | 1.602·10-19 |
| d*E*g/d*T* (1/K) | -0.0002677 |

1. Use an iterative method, such as the one described in Problem 7.4, to calculate enough I-V points to estimate the maximum power point. After a couple iterations, it yields:

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **V (V)** | **Iguess (A)** | **I (A)** | **Error** | **P (W)** |
| **Isc** | 0.0 | 8.50 | **8.50** | 0.0% | 0 |
| **Voc** | **38.8** | 0 | -6E-06 |  | 0 |
| Initial guess | 31.0 | 8.14 | 8.14 | 0.0% | 253 |
|  | 31.2 | 8.12 | 8.12 | 0.0% | 253 |
|  | 31.3 | 8.10 | 8.10 | 0.0% | 254 |
|  | 31.5 | 8.07 | 8.07 | 0.0% | 254 |
|  | 31.6 | 8.05 | 8.05 | 0.0% | 254.6 |
|  | 31.8 | 8.02 | 8.02 | 0.0% | 255.0 |
|  | 32.0 | 7.99 | 7.99 | 0.0% | 255.2 |
|  | 32.1 | 7.95 | 7.95 | 0.0% | 255.3 |
| **Pmax** | **32.3** | 7.92 | **7.91** | 0.0% | **255.4** |
|  | 32.4 | 7.88 | 7.87 | 0.0% | 255.3 |
|  | 32.6 | 7.83 | 7.83 | 0.0% | 255.1 |
|  | 32.7 | 7.79 | 7.78 | -0.1% | 254.7 |
|  | 32.9 | 7.74 | 7.73 | -0.1% | 254 |
|  | 33.0 | 7.68 | 7.67 | -0.1% | 254 |
|  | 33.2 | 7.62 | 7.61 | -0.1% | 253 |

The maximum power point thus obtained (255.4 W) has a -1.4% difference with respect to the value provided by the manufacturer.

**Problem S7.7** The solution is available as a Jupyter notebook at this book’s online repository.

**Problem 7.8**

The PV array is composed of 3 strings of 10 modules in series each, so *N*P,m = 3 and *N*S,m = 10. If every module in the array is assumed to operate under the same irradiance and temperature, we can describe the I-V curve of the whole array using the single-diode model. Model parameters are obtained from those of the module as in Eq. (7.9):

Effective irradiance *G*ef is estimated from in-plane irradiance *G*(*β*,*α*) after accounting for soiling, incidence angle and spectral losses, for instance using Eq. 7.42. Assuming the modules are clean and neglecting the spectral mismatch, which is very small in c-Si modules:

where *θ*i is the angle of incidence of direct light on the module, *B*(*β*,*α*) = *G*(*β*,*α*) - *D*(*β*,*α*) = 900 – 100 = 800 W/m2 and *F*IAM,B and *F*IAM,D are the incidence angle modifiers given by Eqs. 7.46 and 7.47 for direct and diffuse components, respectively. Since the modules are facing South, the angle of incidence at noon is the difference between the zenith angle *θ*Z and the module tilt *β*: *θ*i = *θ*Z*‑ β*= 30°‑15° = 15°. This angle is too low to show a significant optical loss if we assume the typical value of *a*r = 0.16 for modules with a standard glass front sheet:

The incidence angle modifier for the diffuse fraction in Eq. 7.47 assumes an isotropic distribution of the irradiance on the sky dome, so it only depends on the module tilt angle*β =* 15° = π/12:

Thus,

Cell temperature can be estimated using the Sandia Array Performance Model (Eqs. 7.38 and 7.39). Since the array modules are completely integrated on the rooftop surface, we can consider the model coefficients for the “Insulated back” case in Table 7.3: *a*= -2.81, *b*= -0.0455 and Δ*T*[°C] = 0. Then:

Then, we can translate the single-diode model parameters of the array at STC to the operating conditions just calculated using the same methodology of Problem 7.6:

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Array single-diode model parameters** | **At STC** | **Methodology** | **At operating conditions** | **Methodology** |
| n | 1 | Same as module | **1** | Indep. of G, T |
| IL(Gef,Tc) | 31.74 | Eq. 7.2 | **28.62** | Eq. (7.27) |
| I0(Tc) | 7.65·10-11 | Eq. 7.3 | **2.57·10-7** | Eq. (7.29) |
| RP(Gef) | 517 | Eq. 7.5 | **583** | Eq. (7.31) |
| RS | 0.697 | Eq. 7.4 | **0.70** | Indep. of G, T |
| **Other parameters** |  | | | |
| VT(Tc) |  | | 0.0306 | Eq. (7.28) |
| Eg(Tc) |  | | 1.104 | Eq. (7.30) |
| NS,m\*Ns\*n\*VT |  | | 18.38 |  |
| **Data** |  | | | |
| αIsc(1/K) | 0.0003 |  | | |
| kB(J/K) | 1.381·10-23 |
| kB(eV/K) | 8.62·10-5 |
| q(C) | 1.602·10-19 |
| d*E*g/d*T* (1/K) | -0.0002677 |
| NS | 60 |

Using the simple iterative process described in Problem 7.4, we can estimate the maximum power point at:

|  |  |
| --- | --- |
| ***V*mp** | 272 V |
| ***I*mp** | 26.26 A |
| ***P*max** | 7.14 kW |

**Problem 7.9** Calculate the minimum value of the voltage at the maximum power point of a photovoltaic module at STC, so that it is able to adequately charge a 30 V lead-acid battery in a location where the ambient temperature can reach 40 °C. The thermal behavior of the module is characterized by NMOT = 45 °C and *β* = -0.24%/°C.

The voltage of a module at STC is reduced as the cell temperature rises. We can use Eq. 7.36 to estimate module temperature:

which can be considered a reasonable approximation of cell temperature *T*c. Then, we use the linear relationship between temperature and voltage to estimate how much VMP,STC will decrease when the module operates at the calculated temperature. Using Eq. (7.24) and assuming a value of irradiance similar to STC:

We can take the approximation that *V*mp ≃ 0.8· *V*OC to write:

**Problem 7.10** If you had to select a PV module for a residential rooftop system installation with nearby shadings, discuss the type of solar cell you would choose: monofacial full-sized PERC solar cells, monofacial half-cut cells or bifacial solar cells.

Bifacial modules can increase the energy collected by a solar panel due to albedo irradiance. However, when the modules are installed on a residential rooftop, there is a very small gap behind the back of the module so there is a very small amount of reflected irradiance. Therefore, the use of more expensive bifacial modules is not justified.

The use of half-cut cells make a module less sensitive to partial shading when it affects only one half of the module, either top or bottom. Since the rooftop system is said to be affected by nearby shadings, it is expected that the use of this type of solar cells will provide a significant energy gain annually. Furthermore, in practice manufacturers can usually obtain a 2.5% gain in module power when using half-cut cells instead of full cells. Thus, monofacial half-cut cells are probably the best choice.

**Problem 7.11**

1. There are 8 panels in the array and every panel is composed of 3 string blocks, so *N*TB = 8×3 = 24. The shadow covers 1/3 of the array, so *F*GS = 1/3. The 3 string blocks of every panel (8) are affected by the shadow, so *N*SB = 8 × 3 = 24. Using Eq. (7.52):

Meaning that almost all the potential array power is lost due to a shadow that covers only 30% of the area.

1. In this case, the shadow covers the same fraction of the area but there are fewer string blocks affected, so *N*SB = 3 × 2 + 2 = 8, so:

Meaning that the power loss has been greatly reduced because of the large number of string blocks unaffected.

1. Now every panel has two different sub-matrices combined in parallel, so the partial shading on each half module does not limit the current on the other half. Thus, power losses are independently calculated on each half, and then averaged. In each string of half modules: *N*TB,top = *N*TB,bottom = 8×3 = 24.

If we consider the first case (Fig. 7.25, top), the horizontal shadow that covers 1/3 of the array is located on the bottom half only, so *F*GS,top = 0 and *F*GS,bottom = 2/3; also, *N*SB,top = 0 and *N*SB,bottom = 24:

So the combined loss is ***F*ES =** (*F*ES,top+*F*ES,bottom)/2 = **49.3%**. This is half the power loss that was obtained with full-sized cells.

If we consider the second case (Fig. 7.25, bottom), the shadow covers both halves of the array evenly, so *F*GS,top = *F*GS,bottom = 1/3 and *N*SB,top = *N*SB,bottom = 8:

Thus, no power gain is obtained with respect to the case with full cells.

**Problem 7.S12**

SmartCalc.CTM setup files for the three module configurations are available at this book’s online repository. Note that SmartCalc.CTM needs version 9.8 (R2020a) of the MATLAB Runtime and it may require to be run using Administrator privileges.

Initially, we obtained the peak power for the **reference case**:

* Load the template file: “60 M6 full cell HJT module round ribbons glass-glass.xml”
* At the Cell tab, load cell data for “M6 PERC 9 MBB full cell 22.7%.xml”
* At the Module Layers tab, be sure to load standard back cover data without reflectors at the cell spacings: “Glass 2.0mm.xml”
* At the CTM Analysis tab, click the “Start Analysis” button to run the optical-electrical simulation of the current module setup in order to estimate *P*max at STC for the reference case: *P*max,STC = 348.04W with a module efficiency of 19.58%.

1. **120 half-cut cells**:

* First, modify the layout of the module:
  + At the Module Layout tab, load module layout data for “120 half cells.xml”.
  + Modules with half-cut cells include distributed smaller junction boxes at the center of the module: at the same tab, load junction box data “Split\_Junction\_Box.xml”
* Then, modify the characteristics of the solar cells:
  + at the Cell tab, load cell data for “M6 PERC 9 MBB half cell 22.7%.xml”
* Run the simulation again: *P*max,STC = 366.35W, 19.69% eff. This is a power gain of **5.3%**.

1. 60 M6 full PERC cells module with **reflectors at cell spacings**:

* Load the template file: “60 M6 full cell HJT module round ribbons glass-glass.xml”
* At the Cell tab, load cell data for “M6 PERC 9 MBB full cell 22.7%.xml”
* At the Module Layers tab, be sure to load standard back cover data without reflectors at the cell spacings: “Glass 2.0mm.xml”
* Run the simulation again: *P*max,STC = 352.91W, 19.86% eff. This is a power gain of **1.4%** with respect to the 60-full-cell module of the reference case.