4.2. Modeling of PV Generators

Photovoltaic generators contain thousands and thousands of photovoltaic cells. Once integrated into an electrical circuit, each cell converts the incoming solar irradiation (direct and indirect) into an electric current. Neglecting wiring, converter losses, and power mismatch, the generated power of PV systems is the number of all included cells multiplied by the generated power of a single cell. This assumption is useful to summarize all the interconnected PV cells to derive the mathematical model of the overall PV generator for systems analysis and control design.

The basic units of a PV generator are the PV modules, also called solar panels. A standard PV module contains 48 to 73 cells in series connection mounted in a framework for protection and installation. PV generators are commonly assembled by configurations of modules in series and parallel. Solar modules are connected in series to increase the output voltage, frequently referred to as a "string." PV strings in a parallel connection form an array in which the power capacity can be built up to thousands or even millions of a watt. In large-scale PV systems that take over more power plant tasks, an array is divided into multiple subarrays.

The mathematical model of the PV generator results from the aggregation of all PV modules described by the model of a single cell where the current and voltage are suitably multiplied. For this, the single cell is modeled by an equivalent circuit consisting of an irradiation-dependent current source, a model of the diode D, and shunt resistors R_h, as shown in Figure 4.4. The irradiation S with the physical unit $\mathrm{W/m^2}$ is related to the direct (normal to the PV cell array) and the diffuse irradiation. Application of Kirchhoff's

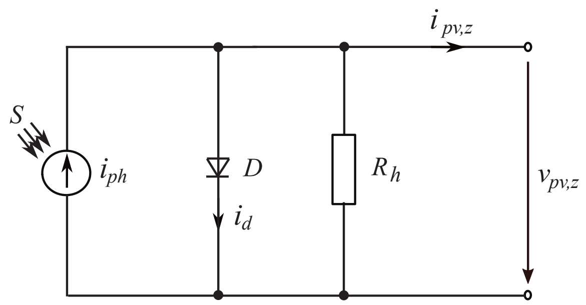

Figure 4.4: Simplified single-diode model (SSDM) of a PV cell

circuits laws results in

$$i_{pv,z} = i_{ph} - i_d - \frac{v_{pv,z}}{R_h}\,, \tag{4.1}$$

with $i_{ph,z}$ and i_d as the light and diode current, where $v_{pv,z}$ denotes the output voltage of a single PV cell. The I-V characteristic of a photovoltaic cell is determined by the diode current as nonlinear function of the PV terminal voltage $v_{pv,z}$ given by

$$i_d = i_s\Big[e^{\frac{v_{pv,z}}{A_n\, v_{T,STC}}} - 1\Big]\,, \quad v_{T,STC} = \frac{k\, T_{c,STC}}{q}\,, \tag{4.2}$$

where i_s represents the saturation current of the diode's diffusion effect

$$i_s = \frac{i_{ph} - \frac{v_{oc,STC}}{R_h}}{e^{\frac{v_{oc,STC}}{A_n\, v_{T,STC}}} - 1} \tag{4.3}$$

with $v_{oc,STC}$ as open-circuit voltage of the diode model at standard test conditions (STC) and $v_{T,STC}$ = 25.7 mV as thermal voltage of p-n junction at STC. The others parameters are the shunt resistor R_h to model the cell losses, k as the Boltzmann constant with $k = 1.381 \times 10^{-32}$ J/K, A_n as the constant ideality factor and elementary charge $q = 1.602 \times 10^{-19}$ As. The irradiation and temperature dependence of light current i_{ph} and open-circuit voltage v_{oc} is given by the relations

$$i_{ph} = \frac{S}{S_{STC}} i_{ph,sc,STC} \left(1 + \alpha_T \left(T_c - T_{c,STC}\right)\right), \tag{4.4}$$

and

$$v_{oc} = v_{oc,STC} \left(1 + \beta_T \left(T_c - T_{c,STC}\right)\right), \tag{4.5}$$

where S denotes the instance irradiation value and T_c the actual operation cell temperature. The constant S_{STC} denotes the irradiation at STC with $S_{STC} = 1000$ W/m^2, and $i_{ph,sc,STC}$ denotes the short-circuit current at STC. The temperature-dependent models (4.4) and (4.5) contain α_T and β_T as temperature coefficients and the value $T_{c,STC} = 298°$K as the temperature at STC. Thus, the PV cell model results from eq. (4.1) - (4.5) and will be summarized as

$$i_{pv,z} = i_{ph}(S, T_c) - i_s(S, T_c) \left[e^{\frac{v_{pv,z}}{A_n\, v_{T,STC}}} - 1 \right] - \frac{v_{pv,z}}{R_h}\,. \tag{4.6}$$

Here, the quantities $i_{ph}(S, T_c)$ and $i_s(S, T_c)$ are specified with the dependent variables to better distinguish them from the constant model parameters. Example of physical parameter, required to calculate the proposed PV cell model are given in App. D in Table D.2 with the STC values listed in Table D.1.

To calculate the PV generator from individual cells, we assume a single PV module with all cells connected in series denoted as $N_{cell,s} = N_{cell}$. The individual modules are in turn connected in series (PV strings) and in parallel to a PV generator, where $N_{mod,p}$ denotes the number of modules in parallel and $N_{mod,s}$ the number of modules in series. Thus, the PV generator is composed in total of $N_s = N_{cell,s}\, N_{mod,s}$ PV cells in series and and these series connections are connected N_p-fold in parallel where $N_p = N_{mod,p}$. The aggregation of all cells in one PV generator is shown in Figure 4.5. Corresponding mathematical

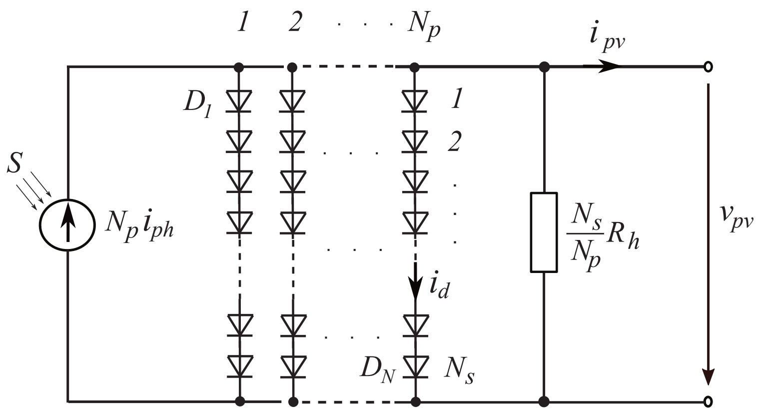

Figure 4.5: Equivalent circuit of a PV generator aggregated from $N = N_s N_p$ single diode models

model of the PV generator with the terminal current

$$i_{pv} = N_p\, i_{pv,z} \tag{4.7}$$

and terminal voltage

$$v_{pv} = N_s\, v_{pv,z} \tag{4.8}$$

is given as

$$i_{pv} = f_{pv}(v_{pv}) = N_p\, i_{ph}(S, T_c) - N_p\, i_s(S, T_c)\Big[e^{\frac{v_{pv}}{N_s\, v_{T,STC}\, A_n}} - 1\Big] - \frac{N_p}{N_s}\frac{v_{pv}}{R_h}\ , \tag{4.9}$$

where i_s calculated by (4.3) and i_{ph} (4.4).

The function curves of (4.9) shown in Figure 4.6 and Figure 4.7 based on the parameters of a 3-MW PV generator with monocrystalline silicon solar cells given in Table D.3. Clear to recognize is the characteristic property of a

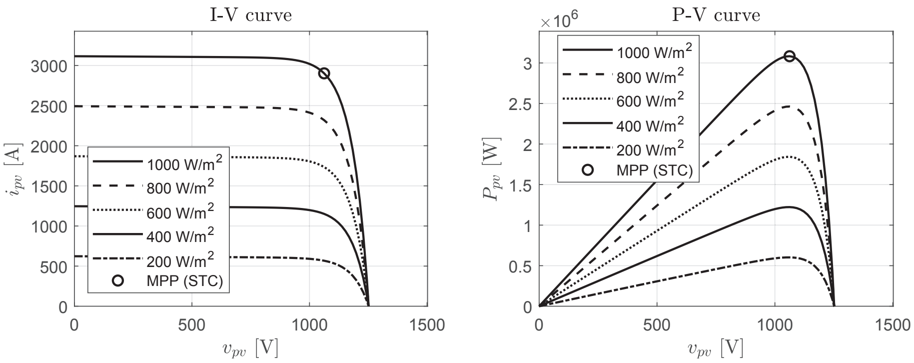

Figure 4.6: Aggregated I-V and P-V curve of a 3083 kW (related to STC) power plant with constant cell temperature $T_{c,STC} = 25°\text{C}$ under variation of irradiation $S = \{200\text{W/m}^2, 400\text{W/m}^2, 600\text{W/m}^2, 800\text{W/m}^2, 1000\text{W/m}^2\}$

PV generator as a current source in both I-V curves. Below the sum of diode forward voltages of approx. 900V, the current is almost equal for constant irradiation and increases linearly in that region with increasing irradiation of $S_{STC} = \{200\text{W/m}^2, \ldots, 1000\text{W/m}^2\}$ as long as the PV voltage v_{pv} is below the sum diode forward voltage. If v_{pv} exceeds the threshold of forward voltages, the

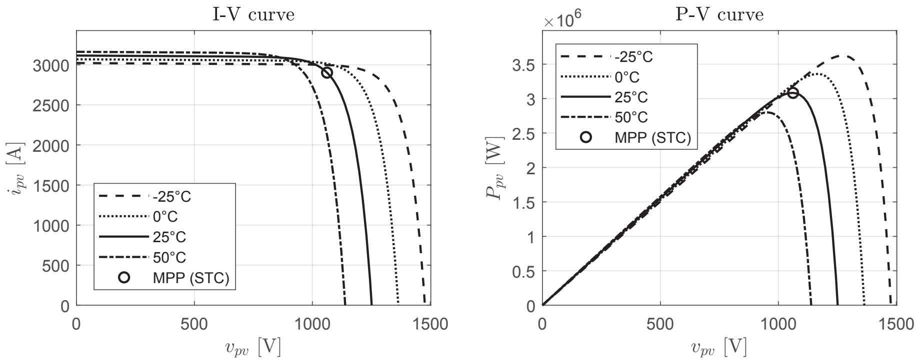

Figure 4.7: Aggregated I-V and P-V curve of a 3083 kW (related to STC) power plant with constant irradiation $S_{STC} = 1000\text{W/m}^2$ under variation of $T_c = \{0°\text{C}\ , 25°\text{C}\ , 50°\text{C}\}$

current drops significantly until the current is zero at the open-circuit voltage. As expected, this behavior is represented by a linear increase in power for the P-V curves until a maximum power point (MPP) is reached. By varying the radiation, a slight variation of the MPP related to the PV voltage v_{pv} can be seen in Figure 4.6 in the P-V diagram. The variation of the MPP is significantly greater with changing the PV cell temperature. In Figure 4.7 a significant shift of the MPP in the lower voltage region can be seen with rising temperature from 0 to 50 degrees. Also to see that the MPP value decreases with increasing temperatures.

To hold the point of maximum power regardless of the current temperature and irradiation, so-called MPP tracker is used. As a higher-level controller, the MPP tracker calculates the voltage reference value of the lower-level v_{pv} voltage controller in order to be able to follow the point of optimum power output even with variable irradiation and cell temperature. Thereby the PV voltage is adjusted through a DC-DC converter.