OPTIMUM DC OPERATING VOLTAGE FOR GRID-CONNECTED PV PLANTS
Choice of V_{MPP} for Measurement of Efficiency and $V_{MPP-STC}$ at PV Plants for Grid-Connected Inverters with a wide DC Input Voltage Range

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ABSTRACT:
For most inverters manufacturers indicate quite a wide range (V_{MPPmin} ... V_{MPPmax}) for the allowable DC voltage V_{MPP} at the maximum power point (MPP), at which the inverter operates well and has no problems to find the MPP on the I-V curve of a PV array. Often also a minimum and a maximum operating voltage (V_{Omin} , V_{Omax}) are given, at which the inverter can operate, but does not find the correct MPP, where $V_{Omin} < V_{MPPmin}$ and $V_{Omax} > V_{MPPmax}$. Sometimes also a maximum DC-input voltage V_{DCmax} is indicated, which may not be exceeded under open circuit conditions (OC) even at the lowest possible module temperature T_{Cmin} . For inverters with consistent specifications $V_{DCmax} > V_{Omax} > V_{MPPmax}$ and V_{DCmax} is considerably greater than V_{MPPmax} . However, some manufacturers give the same value for V_{MPPmax}, V_{Omax} and V_{DCmax}, which does not make much sense in practical PV plants. For practical applications the question arises at which values of V_{MPP} an inverter should reasonably be tested and in which interval the STC array voltages $V_{MPPA-STC}$ (at the MPP) and $V_{OCA-STC}$ (at open circuit conditions) of a PV plant should be chosen.

In this contribution, at first the P-V-curves of a PV array at different irradiances and temperatures are considered. Then, different voltage factors are defined to describe the influence of temperature, irradiance and the voltage difference between the MPP and the open circuit voltage. Then, using the available voltage values indicated on the inverter data sheet, the minimum and the maximum reasonable MPP voltages V_{MPP} of a PV plant with this inverter are determined, which should be used in practical operation and at which the behaviour of the inverter should be tested. The design procedure is then illustrated by some numerical examples for two commercial inverters.

KEYWORDS: Inverter, DC voltage, Operation, Grid-Connected.

1. Definition of symbols used

For a clear distinction of the different voltage and power values some quantities with partially combined subscripts are used, that are defined here for better understanding:

Main symbols:

V	voltage
P	power
G	irradiance [W/m^2]
T	temperature

Subscripts:

MPP	maximum-power-point
STC	standard test conditions (G = 1kW/m^2, cell temperature 25°C)
OC	open circuit
A	array
C	cell-, module- (T_C = cell-/module temperature)
O	operation
LI	at low irradiance (e.g. 0,1·G_{STC})
min	minimum
max	maximum

Most important symbols in detail:

General symbols:

G_{STC}	irradiance at STC (1 kW/m^2)
G_{LI}	Lowest irradiance, at which the plant should still operate (e.g. 0.1·G_{STC})
T_{STC}	STC-reference temperature, at which rated PV array power P_o is defined (25^{o}C)
T_{Cmax}	maximum expected cell (module) temperature of the PV array
T_{Cmin}	minimum expected cell (module) temperature of the PV array

Symbols for quantities of the PV-Plant:

$V_{MPPAmin}$	minimum MPP-voltage of the PV array at G_{STC} and T_{Cmax}
$V_{MPPA-STC}$	MPP-voltage of the PV array at STC ($V_{MPPAmin}/k_{TCmax} < V_{MPPA-STC} < V_{MPPAmax}$)
$V_{MPPAmax}$	maximum MPP-voltage of the PV array (realistic mostly: at STC, i.e. $V_{MPPAmax} = V_{MPPAmax-STC}$)
$V_{MPPAmax-STC}$	maximum MPP-voltage of the PV array at STC
$V_{OCAmin-STC}$	minimum open circuit voltage of the PV array at STC
$V_{OCA-STC}$	open circuit voltage of the PV array at STC ($V_{OCAmin-STC} < V_{OCA-STC} < V_{OCAmax-STC}$)
$V_{OCAmax-STC}$	maximum open circuit voltage of the PV array at STC
$V_{OCA-TCmin}$	maximum open circuit voltage of the PV array at G_{STC} and T_{Cmin}

Symbols for quantities of the inverter:

V_{Omin}	minimum operating voltage of the inverter indicated by manufacturer (turn-off voltage)
V_{MPPmin}	minimum MPP voltage of the inverter indicated by manufacturer
V_{on}	turn-on voltage of the inverter (indication by manufacturer desired, $V_{MPPmin} < V_{on} < k_{LI} \cdot V_{OCAmin-STC}$)
V_{MPPmax}	maximum MPP voltage of the inverter indicated by manufacturer
V_{Omax}	maximum operating voltage indicated by manufacturer (inverter operating, but no MPP-tracking)
V_{DCmax}	maximum input voltage according to manufacturer at open circuit (no operation, no damage)

2. Behaviour of PV arrays at different irradiances and temperatures

Instead of the well-known I-V-curves of PV arrays, diagrams with power vs. voltage P=f(V) can also be used, that are better suited for the discussion of these problems. Like I-V-curves P-V curves depend on irradiance G in the array plane and cell- or module temperature of the PV array. An inverter does not always operate at the MPP, but often somewhat besides it and then takes only $P_{DC} \leq P_{MPP}$ from the PV array (see fig. 1).

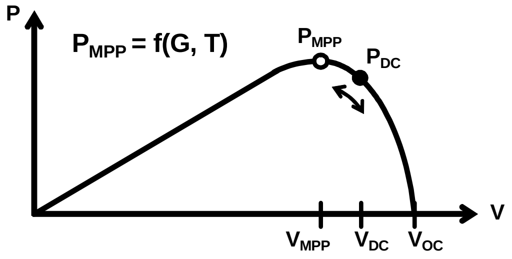


Fig. 1: The P-V-curve of a PV array depends on irradiance G into the array plane and on cell- or module temperature T_C. Thus also maximum power P_{MPP} of the PV array at the maximum power point (MPP) of the array depends on G and T_C .

Fig. 2 shows the P-V-curve of a PV array at STC. At the same irradiance G_{STC}, but lower cell temperatures, the values of P_{MPP} und V_{MPP} increase (see fig. 3). On the other hand at the same irradiance G_{STC}, but higher cell temperatures, P_{MPP} and V_{MPP} decrease (see fig. 4).

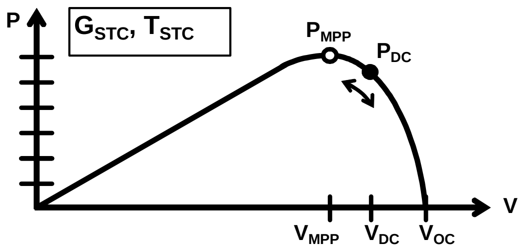


Fig. 2: P-V-curve of a PV array at standard test conditions (STC), G = G_{STC} = 1 kW/m^2, cell temperature T_C = 25°C.

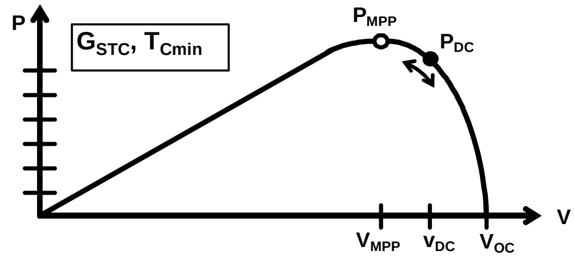


Fig.3: P-V-curve of a PV array at G_{STC} = 1 kW/m^2 and minimum expected cell temperature T_{Cmin} (e.g. -10°C for plants in moderate climates at lower locations).

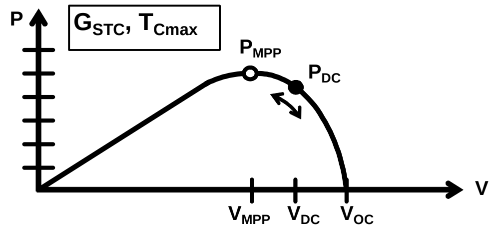


Fig. 4: P-V-curve of a PV array at G_{STC} = 1 kW/m^2 and maximum expected cell temperature T_{Cmax} (e.g. 55°C to 65°C for plants in moderate climates at lower locations).

If at the highest expected cell temperature a sudden decrease of the irradiance occurs (e.g. under cloudy conditions, $G_{LI} \approx 0.1 \cdot G_{STC}$), P_{MPP} and V_{MPP} decrease even more (fig. 5). As usually cell temperatures are a little lower than T_{Cmax} under these weather conditions, somewhat lower values for T_{Cmax} may be realistic.

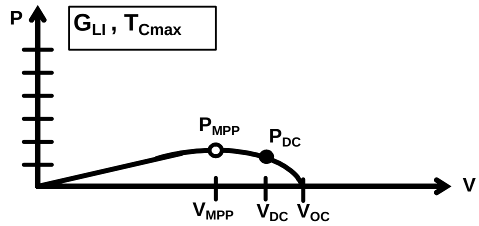
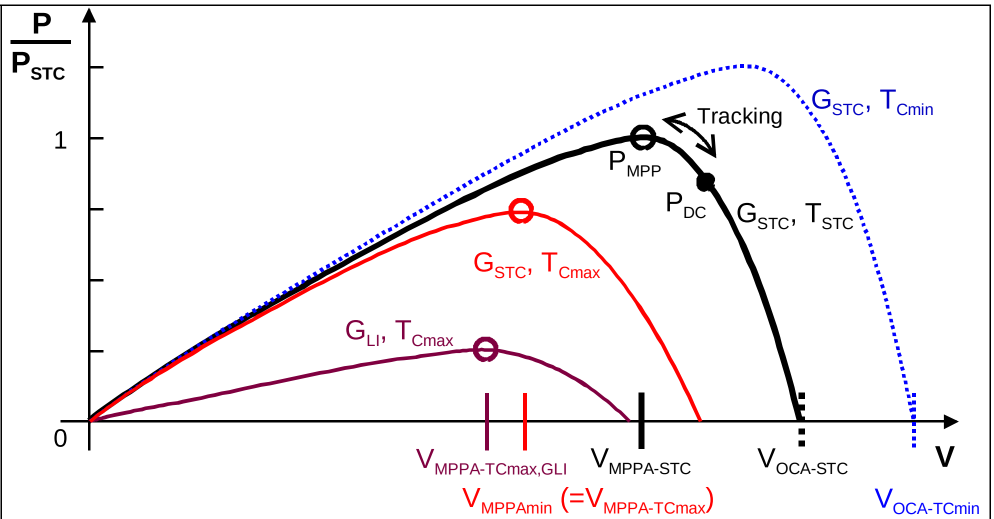


Fig. 5: P-V-curve of a PV array under hot, but cloudy weather conditions after a sudden drop of irradiance down to $G_{LI} < G_{STC}$.

Fig. 6:
Overview of the resulting P-V-curves of a given PV array under different irradiance (G) and temperature (T) conditions. Designations of symbols and subcripts according to chapter 1.



3. Definitions of the relevant voltage factors (with indication of typical values)

Based on fig. 2 to 5, different voltage factors can be defined referring to the corresponding voltages at STC:

The voltage at the MPP is lower than under open circuit conditions, therefore it can be defined:

MPP voltage factor:

$$\mathbf{k_{MPP} = V_{MPP-STC} / V_{OC-STC}} \quad (1)$$

Typical values for k_{MPP} :
crystalline modules with FF ≈ 75%: $k_{MPP} \approx 0.8$
amorphous modules with FF ≈ 55 - 60%: $k_{MPP} \approx 0.7$

At low temperatures and G_{STC}, V_{OC} is higher than at STC, therefore it can be defined:

Low temperature voltage factor:

$$\mathbf{k_{TCmin} = V_{OC-TCmin} / V_{OC-STC}} \quad (2)$$

Typical values for k_{TCmin} in moderate climates ($T_{Cmin} \approx$ -10°C and 1000 W/m^2): $k_{TCmin} \approx 1.15$

Recommended value for alpine plants (lower T_{Cmin}, G_{max} higher than G_{STC}): $k_{TCmin} \approx 1.2$

Recommended value for high-alpine plants for the same reasons: $k_{TCmin} \approx 1.25$

For amorphous modules manufacturers often do not give exact indications. Temperature dependency is lower than with crystalline modules, but during initial degradation the voltages may be higher. Therefore it makes sense to use about the same factors as for crystalline modules, if no further data are available.

At high temperatures and G_{STC}, MPP voltage decreases compared to STC, therefore it can be defined:

High temperature voltage factor:

$$\mathbf{k_{TCmax} = V_{MPPA-TCmax} / V_{MPPA-STC}} \quad (3)$$

Typical value for crystalline modules at $T_{Cmax} \approx 60$°C for G_{STC} : $k_{TCmax} \approx 0.86$

For the same reason as indicated above, it makes sense to use about the same factors as for crystalline modules also for amorphous modules, if no further data are available for them.

At low irradiance at T_{STC} open circuit voltage V_{OC} at $0{,}1 \cdot G_{STC}$ is lower than at G_{STC}, therefore:

Low irradiance voltage factor:

$$\mathbf{k_{LI} = V_{OC-GLI} / V_{OC-STC}} \quad (4)$$

Typical value for $G_{LI} \approx 0{,}1 \cdot G_{STC}$: $k_{LI} \approx 0.88$

4. Correct choice of operating voltage for PV plants

As far as DC voltages are concerned, most inverter manufacturers do not give sufficient information needed for proper PV plant design. Missing data must be completed in a way that a safe operation of the plant is possible.

If a value for V_{DCmax} is missing, it is assumed that $V_{DCmax} = V_{Omax}$.

If a value for V_{Omax} is missing, it is assumed that $V_{Omax} = V_{MPPmax}$.

In order to provide a large DC input voltage range to the designer of the PV plant, manufacturers should specify their products as precisely as possible also as far as DC voltages are concerned!

A PV plant is designed in an optimum way, if

- even in the worst case (mostly at G_{STC} = 1kW/m^2 and minimum cell temperature T_{Cmin}, at plants at higher altitudes also at somewhat higher G-values), at the open circuit voltage $V_{OCA-TCmin}$ no defect occurs.
- the inverter always starts operation at all V_{OC}-values encountered under real operating conditions.
- The inverter always finds the actual MPP at all expected V_{MPP} values.

In order to ensure proper dynamic MPP-tracking [1], the minimum MPP-voltage $V_{MPPAmin}$ of the PV plant at the highest expected cell temperature T_{Cmax} has to be a little higher than V_{MPPmin} of the inverter:

$$\mathbf{V_{MPPAmin} = V_{MPPmin} / k_{LI}} \quad (5)$$

When systematic inverter tests are carried out, it makes sense to examine the behaviour of the inverter at this minimum reasonable voltage of the PV array. It must be noted, however, that many inverters have not only a minimum DC-voltage specification, but also a maximum DC-current specification. Therefore a derating of their operating power at low DC voltages may be necessary.

With (3) the minimum MPP-voltage of the PV plant at STC is:

$$\mathbf{V_{MPPAmin-STC} = V_{MPPAmin} / k_{TCmax}} \quad (6)$$

With the typical values for k_{LI} and k_{TCmax} indicated above we obtain:

$$\mathbf{V_{MPPAmin-STC} \approx 1{,}32 \cdot V_{MPPmin}} \quad (7)$$

With (2) the maximum allowable open circuit voltage of the plant at STC becomes:

$$\mathbf{V_{OCAmax-STC} = V_{DCmax} / k_{TCmin}} \quad (8)$$

Using (1) we get for the maximum allowable MPP-voltage at STC:

$$\mathbf{V_{MPPAmax} = V_{OCAmax-STC} \cdot k_{MPP}} \quad (9)$$

Therefore during systematic inverter tests the behaviour of the device at this maximum reasonable operating voltage of the PV array has to be determined. It makes sense to test also the behaviour at other intermediate voltages (e.g. at the average value between $V_{MPPAmin}$ and $V_{MPPAmax}$).

With the typical values indicated for k_{MPP} and k_{TCmin} for lower regions in moderate climates the following approximations can be used:

For crystalline modules : $\mathbf{V_{MPPAmax} \approx 0{,}7 \cdot V_{DCmax}}$ **(10)**

For amorphous modules : $\mathbf{V_{MPPAmax} \approx 0{,}6 \cdot V_{DCmax}}$ **(11)**

For an optimum energy yield a PV plant designer will choose $V_{MPPA-STC}$ in a way that a maximum total efficiency $\eta_{tot} = \eta \cdot \eta_{MPPT}$ is obtained [2], whereas

$$\mathbf{V_{MPPAmin-STC} < V_{MPPA-STC} < V_{MPPAmax-STC} \approx V_{MPPAmax}}.$$

Based on the deliberations presented above, the actually usable DC input voltage range of grid-connected PV inverters is mostly significantly smaller than indicated on the inverter data sheets.

In fig. 7 there is a graphic illustration of the DC voltage range at MPP, in which the operating voltage of a PV array at G_{STC} = 1kW/m^2 must be chosen, in order to match the voltage specifications of a given inverter (indicated below the arrow at the bottom of the figure) without energy losses due to insufficient MPP-tracking or damage by overvoltage on very cold days.

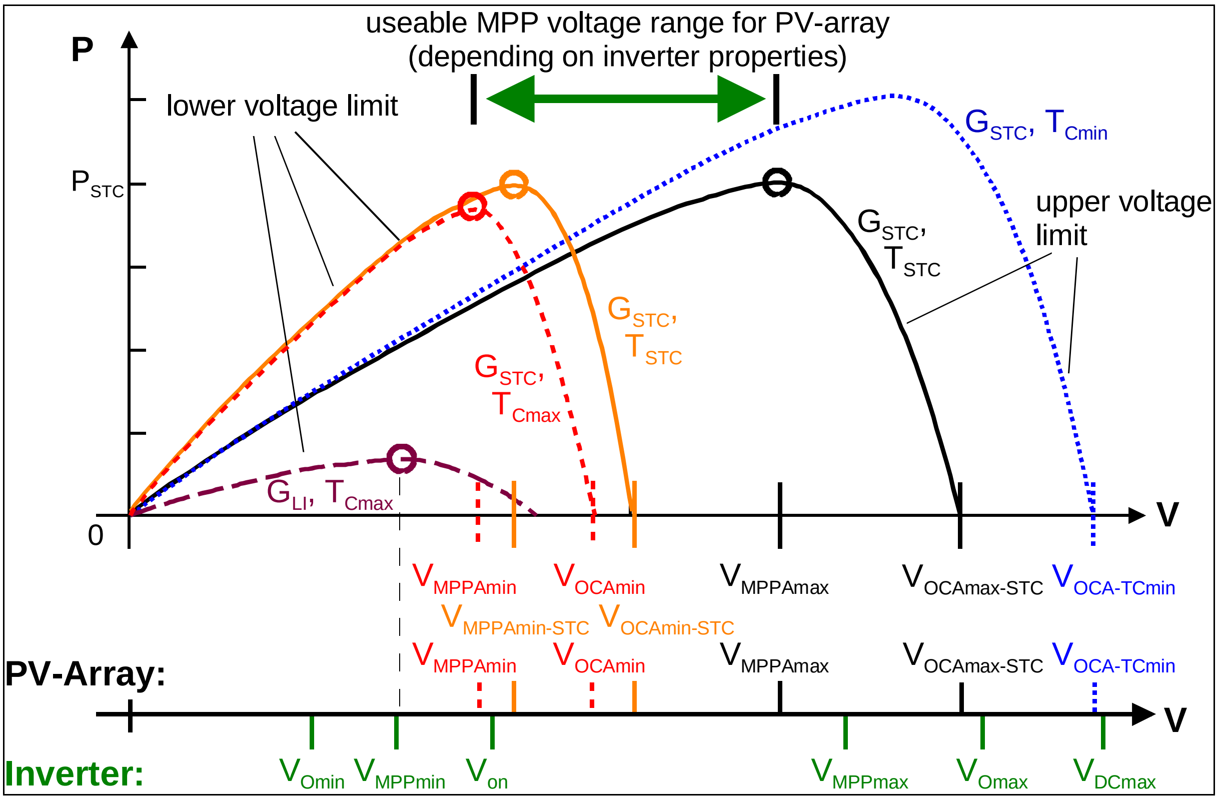


Fig. 7: Usable MPP-voltage range at G_{STC} = 1 kW/m^2 for a PV array (voltage values over the arrow) determined according to the indications on the inverter data sheet (below the arrow)

5. Practical examples

Fronius IG30:

V_{DCmax} = 500 V , V_{MPPmax}= 400 V, V_{MPPmin} = 150 V

With (5) we obtain $V_{MPPAmin} \approx$ 170 V

With (6) or (7) we obtain $V_{MPPAmin-STC} \approx$ 198 V

With (1) we obtain
for crystalline modules $V_{OCAmin-STC} \approx$ 248 V,
for amorphous modules $V_{OCAmin-STC} \approx$ 282 V

With (8) we obtain for plants in moderate climates at low altitudes for $V_{OCAmax-STC} = V_{DCmax} / k_{TCmin} \approx$ 435 V

With (9) or (10) we obtain for crystalline plants in moderate climates at low altitudes: $V_{MPPAmax} \approx$ 350 V

With (9) or (11) we obtain for amorphous plants in moderate climates at low altitudes: $V_{MPPAmax} \approx$ 300 V

Therefore it makes sense during inverter tests to examine the behaviour at $V_{MPPAmin} \approx$ 170 V, at $V_{MPPAmax} \approx$ 350 V and at the average value 260 V.

Sunways NT4000:

V_{DCmax} = 800 V (information from manufacturer obtained by phone, should be included in data sheet),
V_{Omax} = 750 V, V_{MPPmax} = 650 V , V_{MPPmin}= 350 V

With (5) we obtain $V_{MPPAmin} \approx$ 398 V

With (6) or (7) we obtain $V_{MPPAmin-STC} \approx$ 462 V

With (1) we obtain
for crystalline modules $V_{OCAmin-STC} \approx$ 578 V,
for amorphous modules $V_{OCAmin-STC} \approx$ 660 V

With (8) we obtain for plants in moderate climates at low altitudes for $V_{OCAmax-STC} = V_{DCmax} / k_{TCmin} \approx$ 696 V

With (9) or (10) we obtain for crystalline plants in moderate climates at low altitudes: $V_{MPPAmax} \approx$ 560 V

With (9) or (11) we obtain for amorphous plants in moderate climates at low altitudes: $V_{MPPAmax} \approx$ 480 V

Therefore it makes sense during inverter tests to examine the behaviour at $V_{MPPAmin} \approx$ 400 V, at $V_{MPPAmax} \approx$ 560 V and at the average value 480 V.

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[1] H. Häberlin and L. Borgna: "A new Approach for Semi-Automated Measurement of PV Inverters, especially MPP Tracking Efficiency, using a Linear PV Array Simulator with High Stability". 19. EU PV Solar Energy Conference., Paris, 2004.

[2] H. Häberlin, L. Borgna, M. Kämpfer and U. Zwahlen: "Total Efficiency η_{tot} - a new Quantity for better Characterisation of Grid-Connected PV Inverters". 20. EU PV Solar Energy Conference, Barcelona, 2005.

Further information about the research activities of the PV laboratory of HTI (former name: ISB) on the internet: http://www.pvtest.ch.