Simulation and analysis of a shading situation for a grid-connected PV system

by order of Steca Elektronik GmbH, Memmingen

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Content

1 Summary of results and conclusion

The analysis of the two provided connection schemes for 27 example modules with two StecaGrid 2000+ inverters (Master and Slave) and one example string inverter (hereinafter referred to as ESI) produces the result which is to be expected. In the absence of shading, the ESI achieves an almost 2% higher yield than the two StecaGrid 2000+ inverters, due to its higher efficiency. In the actual case in question, in which a dormer casts a shadow on the generator surface in the mornings and evenings, the StecaGrid 2000+ inverters (which use multi-MPP trackers) achieve a higher yield than the ESI (which uses 1 MPP tracker for 3 parallel strings). With an annual energy yield of 4,189.6 kWh, they could feed around 8.2% more energy into the grid than the ESI (3,872.2 kWh)[1]. This difference is due to the ESI's universal shifting of the MPP point in the event of shading.

With an approximately 8.2% higher yield, the connection scheme with the StecaGrid 2000+ inverters clearly shows that the use of a multi-MPPT inverter is worthwhile in the event of shading, even if the difference in efficiency is greater than that of the two tested inverters. Furthermore, the fact that in this shading situation the StecaGrid 2000+ inverters achieve a yield which is only 1.7% lower than in the absence of shading, is indicative of the shading tolerance of the multi-MPPT inverters.

However, it must also be noted that the mismatch losses of the string (ESI) in which 35° modules are connected to 20° modules were not taken into account, so the difference in annual energy yield compared to the StecaGrid 2000+ inverters will be even higher.

[1] With the simulation program PVSYST, the annual energy yield of the SSI (specimen string inverter) in the case of shading is 3810.24 kWh, thereby showing yield losses of around 10% compared to the StecaGrid 2000+.

2 Purpose and description of the reference system

The simulation of the specific annual energy yield of the PV system defined below for two different systems shows which system (different inverters) achieves a higher annual yield. In addition, the system is in a shading situation caused by a dormer (assessment specifications from Steca Elektronik GmbH).

- **System location**

  Munich was selected as the system location, with the following geographical data:

  Longitude: 11.58° Latitude: 48.14° Height above sea level: approx. 520 m

- **Inclination, orientation and size of the PV generator**

  The PV generator faces due south (180°) and comprises 27 modules – for electrical data, see appendix 4.1. Of these modules, 21 are installed on the roof surface with an inclination of 35° and the remaining 6 on the surface of the shed dormer with an inclination of 20°. The ridge of the dormer is approximately 1.5 m high and the distance between the modules and the dormer is 0.5 m on the left and right. This partitioning can be seen in figure 1.

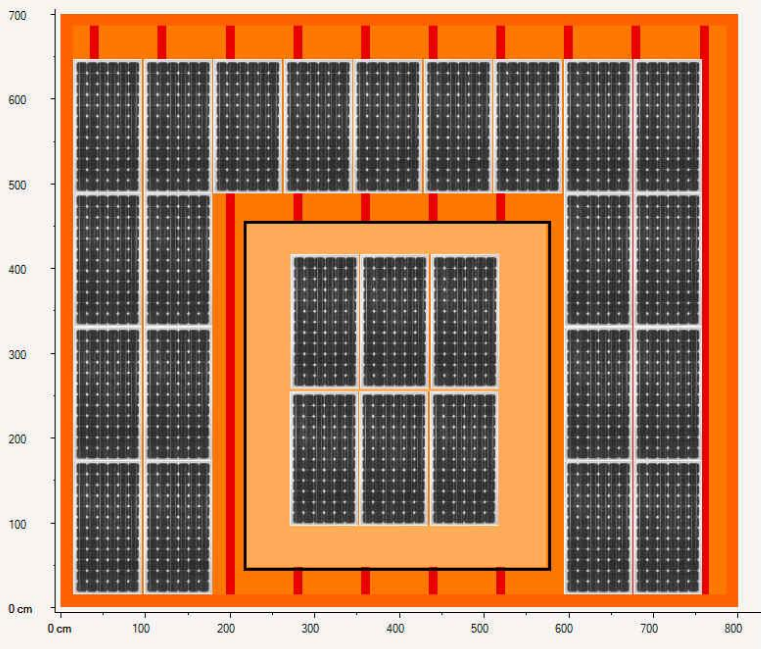

Fig. 1: Distribution of the 27 PV modules on the surface of the specimen roof and the dormer

3 Simulation of the specific annual energy yields of the two systems

3.1 Definition of the two systems

- **Variant 1: string connection scheme with an example string inverter (ESI)**

The inverter (ESI) has an input power of 4,040 W (DC) and a single MPP tracker for all 3 inputs. The remaining electrical parameters are indicated in appendix 4.2. At each of the 3 parallel inputs, 9 modules – as seen in figure 2 – are connected in series.

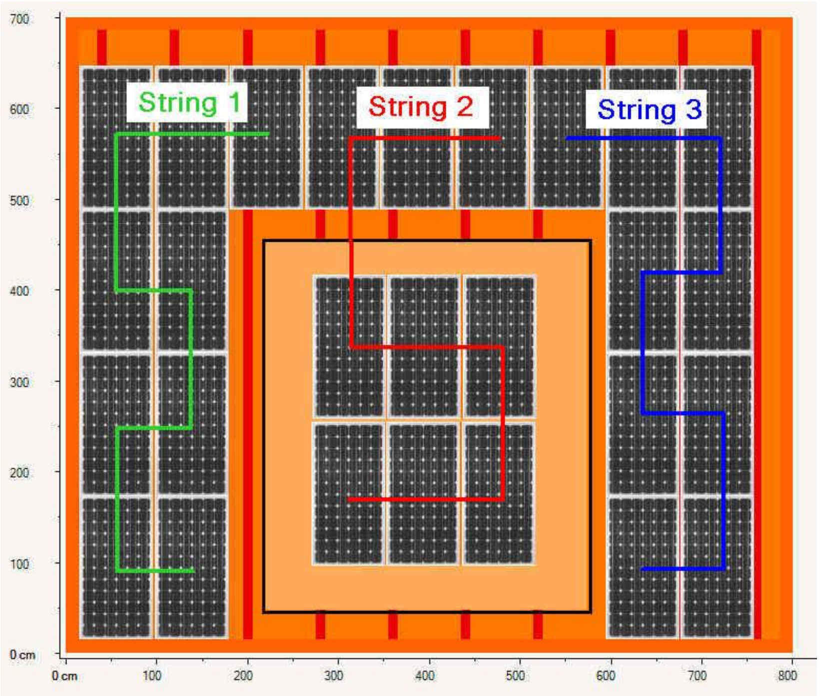

Fig. 2: String connection of the 27 modules on an example string inverter (ESI)

- **Variant 2: string connection scheme with the StecaGrid 2000+ Master and 2000+ Slave inverters**

Each inverter has an input power of 2,150 W (DC) and has 2 inputs; each input has its own MPP tracker. The connection of the strings occurs as depicted in figure 3. Thus, 2 strings, each with 7 modules, are connected to the StecaGrid 2000+ Master and 1 string, also with 7 modules, as well as another with 6 modules, are connected to the StecaGrid 2000+ Slave. The string with 6 modules includes the modules on the dormer (inclination 20°).

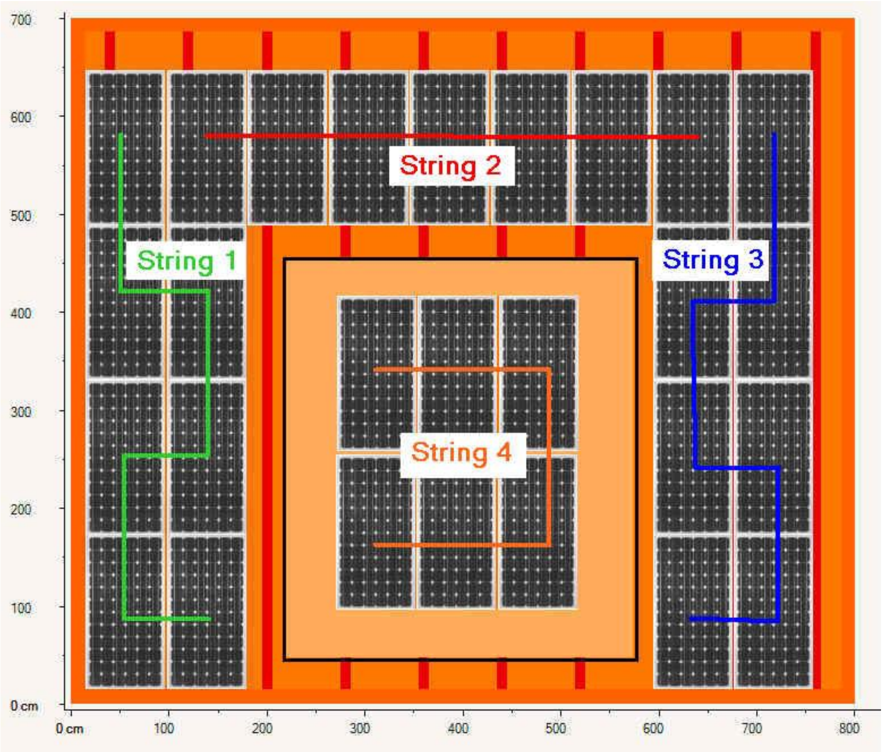

Fig. 3: String connection of the 27 modules on the StecaGrid 2000+ inverters

3.2 Without consideration of the shading situation

- **Variant 1: example string inverter (ESI)**

  For the PV system at the Munich site, with a peak output of 4.32 kWp, an annual energy yield of 4,343.7 kWh is predicted on the basis of the simulation calculation. This corresponds to a specific yield of **1,004 kWh/(kWp per annum)** and a performance ratio of 77.1%. (Connection scheme: two strings with 9 modules at a 35° inclination and one string with 9 modules at 20°).

- **Variant 2: StecaGrid 2000+ Master and Slave inverters**

  For the PV system at the Munich site, with a peak output of 4.32 kWp, an annual energy yield of 2,221.7 kWh is predicted for the 2000+ Master (2.24 kWp) and 2,039.3 kWh for the 2000+ Slave (2.08 kWp) on the basis of the simulation calculation. Therefore, a total energy yield of 4,261 kWh per annum is to be expected. This corresponds to a specific yield of **986.34 kWh/(kWp per annum)** and a performance ratio of 75.2%.

3.3 With consideration of the shading situation

- **Variant 1: example string inverter (ESI)**

  For the PV system at the Munich site, with a peak output of 4.32 kWp, an annual energy yield of 3,872.2 kWh is predicted on the basis of the simulation calculation. This corresponds to a specific yield of **896.34 kWh/(kWp per annum)** and a performance ratio of 70%. Here, however, all 27 modules have an inclination of 35°. Due to this assumption, the actual specific annual yield will be somewhat lower. For the same situation (all modules 35°), the simulation with PVSYST showed a specific annual yield of **882 kWh/(kWp per annum)**. Thus, in this case, yield losses of at least around 11% compared to the unshaded case in section 3.2 are to be expected.

- **Variant 2: StecaGrid 2000+ Master and Slave inverters**

  For the PV system at the Munich site, with a peak output of 4.32 kWp, an annual energy yield of 2,201.7 kWh is predicted for the 2000+ Master (2.24 kWp) and 1,987.9 kWh for the 2000+ Slave (2.08 kWp) on the basis of the simulation calculation. Therefore, a total energy yield of 4189.6 kWh per annum is to be expected. This corresponds to a specific yield of **969.82 kWh/(kWp per annum)** and a performance ratio of around 75%. The losses caused by shading are just 1.7% compared to the unshaded system in section 3.2.

3.4 Programs, deductions and error analysis used

The simulations were conducted with PV*SOL Expert 4.0 (R4) and validated with the programs PVSYST V4.34 and PVscout (version 1.7.2.12123). Regardless of the simulation algorithm, additional deviations occur due to slightly different weather data sets, different inverter efficiency curves and string connections. One defined error is included in all simulation programs because, at present, calculations for two different inclinations within one string cannot yet be realised. Nevertheless, for this string with 6 x 20° and 3 x 35°, the following can be determined: for sun heights below 62.5°, the 20° modules have the lower output and thus define the string current. When the sun is above this height, the current is limited by the 35° modules. However, in Munich, this value is near the maximum sun height of 65.25°. Therefore, if the entire string is assumed to be at 20°, the energy for sun heights above 62.5° is calculated slightly too high, but this only constitutes a small proportion of the total energy yield.

Note:

The yields determined here were calculated on the basis of the technical data of the PV system (modules, inverters, connection, orientation, inclination etc.) and several years of weather data (irradiation, temperature) for the above location. The results were determined by means of a mathematical model calculation. The actual yields of the photovoltaic system can differ, due to fluctuations in the weather, the efficiencies of modules and inverters, as well as other factors. Due to these aspects, as well as tolerances and unforeseeable operating conditions, Solarschmiede GmbH does not, under any circumstances, guarantee the realisation of a predicted energy yield.

4 Appendix

4.1 Electrical data of the example module

Electrical parameters	Values
*Performance specifications (excluding NOCT) under standard test conditions (STC)**	
Rated power (P_{mpp})	160 W
Performance tolerance (ΔP_{mpp})	+5%/ -0%
Guaranteed minimum output (Pmpp min)	160 W
Rated voltage (U_{mpp})	35.6 V
Rated current (I_{mpp})	4.5 A
Open circuit voltage (U_{OC})	43.5 V
Short-circuit current (I_{SC})	5.0 A
Module efficiency	12.5 %
Temperature coefficient α (P_{mpp})	-0.04 %/°C
Temperature coefficient β (I_{mpp})	+0.04 %/°C
Temperature coefficient χ (U_{mpp})	-0.38 %/°C
Temperature coefficient δ (I_{mpp})	+0.04 %/°C
Temperature coefficient ε (U_{mpp})	-0.38 %/°C
Normal Operatring Cell Temperature (NOCT)**	45 °C (+/- 2)
Max. permissible system voltage	1000 V
** Radiation intensity 1,000 W/m², Air Mass 1.5, cell temperature 25°C*	
*** Radiation intensity 800 W/m², ambient temperature 20°C, wind speed 1 m/s*	

4.2 Electrical Data of the example inverter

Parameters	Values
DC-input side	
Maximum power DC	4040 W
Maximum voltage DC	500 V
MPPT voltage range	200 bis 400 V
Maximum input current	20 A
Maximum number of strings (parallel)	3
Number of MPP trackers	1
AC output side	
Nominal output power AC	3800 W
Maximum power AC	3800 W
Maximum output current	18 A
Grid frequency / range	50 Hz / 60 Hz +/- 4.5 Hz
Rated grid voltage / range	220 - 240V / 180 - 260V
Power factor (Cos Phi)	1
Connection AC	single-phase
Performance data	
Maximum efficiency	95.6 %
Maximum european efficiency	94.7 %

4.3 Electrical data of the inverter: StecaGrid 2000+ Master and Slave

	StecaGrid 2000+ D Master	StecaGrid 2000+ Master	StecaGrid 2000+ Slave
DC input data			
MPP voltage	80 V ... 400 V		
Maximum start voltage	410 V DC		
Maximum permissible input voltage	450 V DC (higher voltages can damage the device)		
Minimum input voltage for grid-feeding	80 V		
Minimum input voltage for rated output	132 V		
Maximum permissible input current	2 x 8 A DC (current limited by inverter) or 1 x 16 A DC (parallel inputs)		
Maximum input power	1,075 W (per input) or 2,150 W (2 parallel inputs)		
Derating / limiting	automatic when - input power is higher (> 1.075 kW/input) - the device is not cooled sufficiently - input currents > 2 x 8 A DC or 1 x 16 A (parallel inputs) (higher currents are limited by the equipment and therefore will not damage the inverter)		
AC output data			
Output voltage	190 V AC ... 265 V AC (depending on regional settings)		
Rated output voltage	230 V AC		
Maximum output current	10 A AC		
Maximum output power	2,000 W AC		
Rated output power	2,000 W AC		
Rated frequency	50 Hz		
Frequency	47,5 Hz ... 52 Hz (depending on regional settings)		
Feeding phases	single-phase		
Total harmonic distortion	< 5 % (at maximum output)		
Operating behaviour			
Maximum efficiency	95 %		
European efficiency	93.3 %		93.5 %
MPP efficiency	> 99 %		
Power derating at full power	from 40 °C (Tamb.)		
Switch-on power	20 W		
Standby power	3 W		
Inverter's own consumption (nighttime operation)	1.3 W	1.0 W	0 W