

INFLUENCE OF A SOLAR MODULE'S FILL FACTOR ON THE STATIC MPP TRACKING PERFORMANCE OF SINGLE PHASE PV INVERTERS

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ABSTRACT: Many modern PV modules have a much higher fill factor than the P-V curves used in standard test procedures for PV inverters. A high fill factor makes a PV module more susceptible to MPP tracking losses. Single phase grid connected PV inverters without DC link always have a ripple on the DC side. This ripple makes an ideal MPP tracking impossible, because even if the DC voltage is optimized, the operating point always oscillates around the MPP. A high fill factor increases the losses caused by this effect. This paper shows that these losses can be as high as or even exceed the losses caused by the inverter's conversion efficiency. This is done by data obtained with a simulation model, but also with actual measurements performed on a real PV inverter.

Keywords: Inverter, MPPT Efficiency, Fill Factor

1 INTRODUCTION

In standard test procedures, the MPP tracking performance of a PV inverter is tested with a P-V characteristic having a fill factor of 72%. However, modern PV modules have a fill factor of up to 85%. The peak of such a characteristic is much sharper than the peak of the standard characteristic. As a consequence, even a small deviation from the MPP results in a considerable loss of power.

On the DC side of a grid connected PV array using a single phase PV inverter without DC link, there is always a ripple with twice the line frequency present. Even if the MPP is properly tracked, due to this ripple, the operating point always oscillates around the MPP, leading to a reduction of the tracking performance.

Because of their high fill factor, modern PV modules are far more susceptible to losses caused by this ripple than the standard test curves. In some cases it is possible, that these ripple-induced MPP tracking losses are in the range of the losses caused by the limited conversion efficiency of the inverter.

2 DC RIPPLE OF SINGLE PHASE PV INVERTERS

Before we investigate the problem of the ripple-induced tracking losses, we take a look at how the ripple on the DC side of single phase PV inverters is generated. For this, let's assume that the inverter is connected to a grid with a perfect sinusoidal line voltage and injects a current that is also sinusoidal and in phase with the line voltage.

$$(1) \quad v_{AC} = \sqrt{2} * V_{RMS} * \sin(2\pi * f_{AC} * t)$$

$$(2) \quad i_{AC} = \sqrt{2} * I_{RMS} * \sin(2\pi * f_{AC} * t)$$

with v_{AC} : Instantaneous value of the line voltage
 i_{AC} : Instantaneous value of the injected current
 V_{RMS} : RMS value of the line voltage
 I_{RMS} : RMS value of the injected current
 f_{AC} : line frequency
 t : time

The injected power is the product of current and voltage. With a little trigonometry we get formula (3) which describes the instantaneous value of the injected power in function of the time.

$$p_{AC} = v_{AC} * i_{AC} = 2 * V_{RMS} * I_{RMS} * \sin^2(2\pi * f_{AC} * t)$$

$$(3) \quad \rightarrow p_{AC} = P_{AC} * (1 - \cos(4\pi * f_{AC} * t))$$

with p_{AC} : Instantaneous value of the injected power
 P_{AC} : Injected power ($P_{AC} = V_{RMS} * I_{RMS}$)

As we can see, the injected power oscillates with a frequency that is twice the line frequency. The amplitude of this oscillation is equal to the average value of the injected power. If the inverter has no DC link, this oscillation also appears on the inverter's DC side. Because of this, the inverter has a smoothing capacitor which is basically in parallel to the PV array. This capacitor serves as an energy buffer that reduces the ripple on the DC side. However, the ripple can never be eliminated completely. We will see later, that to achieve a good ripple reduction, in some cases the smoothing capacitor has to have a considerable size.

3 MODELING OF THE PV ARRAY

To simulate the tracking losses caused by the DC ripple, a model for the PV array is needed. Such a model can be found in the European standard EN 50530 [1]. This standard defines methods for measuring the overall efficiency of grid connected PV inverters. It also contains a model that defines the characteristics of the simulated PV array for the test procedures. This model is both simple and flexible. The relation between current and voltage is shown in (4). The relation between power and voltage is shown in (5). For details see EN 50530.

$$(4) \quad i_{PV} = I_{SC} - I_0 \left(e^{\frac{v_{PV}}{V_{OC} * C_{AQ}}} - 1 \right)$$

$$(5) \quad p_{PV} = v_{PV} * i_{PV} = v_{PV} \left[I_{SC} - I_0 \left(e^{\frac{v_{PV}}{V_{OC} * C_{AQ}}} - 1 \right) \right]$$

with i_{PV} : Current of the PV array
 v_{PV} : Voltage of the PV array
 p_{PV} : Power from the PV array
 I_{SC} : Short-circuit current of the PV array
 V_{OC} : Open-circuit voltage of the PV array
 I_0, C_{AQ} : Parameters to adjust the fill factor

Curves calculated with (4) and (5) are an approximation. MPP power, open-circuit voltage and fill factor might deviate slightly from the parameters used for the calculation.

For testing of PV inverters, EN 50530 offers the parameters for a c-Si model with a fill factor of 72%. Alternatively, parameters for a thin film model with a fill factor of 57.6% are provided. As mentioned under section 1, a fill factor of 72% is not representative for modern c-Si modules. Also, a fill factor of 57.6% is too low for many thin film technologies. For the simulations in this paper, curves with fill factors from (approximately) 50% to 85% in steps of 5% as well as the normative fill factors are used. However, not only the fill factor, but also the ratios between MPP voltage and open-circuit voltage (FF_V) respectively between MPP current and short circuit current (FF_I) are important. These values have been taken from EN 50530 and extended with values of actual PV modules. They are listed in Table I. Figure 1 shows the corresponding P-V curves.

Table I: Parameters of the simulated PV arrays

| Fill factor | FF_V | FF_I |
|-------------|--------|--------|
| 50.9% | 67.8% | 75.0% |
| 55.4% | 70.3% | 78.8% |
| 57.8% | 71.6% | 80.7% |
| 60.1% | 72.9% | 82.4% |
| 65.0% | 75.7% | 85.9% |
| 70.0% | 78.6% | 89.0% |
| 72.0% | 79.8% | 90.2% |
| 75.0% | 81.7% | 91.8% |
| 80.0% | 85.0% | 94.1% |
| 85.2% | 88.6% | 96.2% |

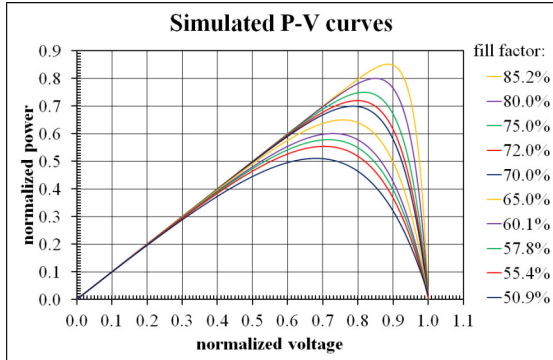


Figure 1: Simulated P-V curves with different fill factors

4 SIMULATION APPROACH

To determine the influence of the DC ripple on the MPP tracking efficiency, this effect must be investigated isolated. To achieve this, a simulation model consisting of a PV array as described under section 3, a smoothing capacitor and an idealized inverter is used. This model is shown in Figure 2.

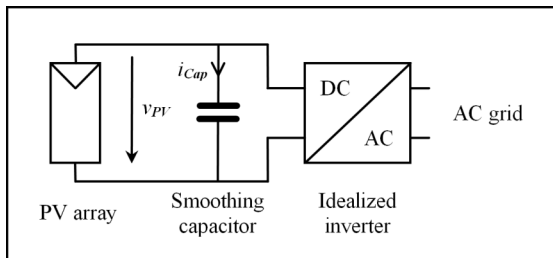


Figure 2: Basic simulation model

The idealized inverter is 100% effective and has no energy storage capabilities. Therefore, this inverters input and output power are exactly the same at any time and are described with (3). The simulation is based on the capacitor voltage which is the integral of the current into the capacitor. Because the capacitor voltage is the same as the voltage of the PV array, it is referred to as v_{PV} .

$$(6) \quad v_{PV} = \frac{1}{C} \int_0^t i_{Cap} dt = \frac{1}{C} \int_0^t \frac{p_{PV} - p_{AC}}{v_{PV}} dt$$

with p_{AC} : Instantaneous value of the power into the AC grid
 p_{PV} : Instantaneous value of the power from the PV array
 i_{Cap} : Instantaneous value of the current into the capacitor
 C : Capacity of the smoothing capacitor

The complete equation can be obtained by inserting (3) and (5) into (6).

$$(7) \quad v_{PV} = \frac{1}{C} \int_0^t \frac{v_{PV} \left[I_{SC} - I_0 \left(e^{\frac{v_{PV}}{V_{OC} C_{AQ}} - 1} \right) \right] - P_{AC} (1 - \cos(4\pi f_{AC} t))}{v_{PV}} dt$$

This integral equation cannot be solved symbolically. But it is possible to solve it numerically. The tracking losses in this paper are based on numerical solutions of this equation, using a simulation in MATLAB and SIMULINK.

5 SIMULATION RESULTS

To visualize the effect of the fill factor on the tracking efficiency, the tracking losses of four exemplary configurations were simulated. They are listed in table II.

Table II: Simulation scenarios

| Scenario | C | P_{MPP} | V_{MPP} |
|----------|----------------|-----------|-----------|
| A | 2'500 μ F | 1'500W | 200V |
| B | 6'800 μ F | 270W | 30V |
| C | 10'000 μ F | 100W | 10V |
| D | 10'000 μ F | 100W | 20V |

Scenario A represents a small string inverter configuration operating at its minimum MPP voltage (we will see later, why this operating point has been chosen). Scenario B represents a typical module inverter configuration with a 72-cell module. Scenario D is a hypothetical configuration with a very small inverter that is connected to only 24 cells (e.g. one bypass diode loop of a 72-cell module). Scenario D is identical to scenario C except for the MPP voltage which is twice as high. We will see that this has a huge impact on the MPP tracking performance.

The simulation results are shown in figure 3 and table III. As can be seen, the string inverter of scenario A has the best tracking performance. Even with a very high fill factor of 85% the losses are less than 0.4%. The losses of the module inverter of scenario B are about 8 times higher. Even with the standard characteristic with a fill factor of 72%, this inverter would lose more than 1.3% of the MPP power. At higher fill factors, the losses can be more than twice as high. Scenarios C and D make a good impression on how sensitive the tracking performance responds to changes of the operating voltage. These scenarios differ only in the MPP voltage.

But where scenario D has an adequate performance, the tracking efficiency of scenario C would be unacceptable for a real application.

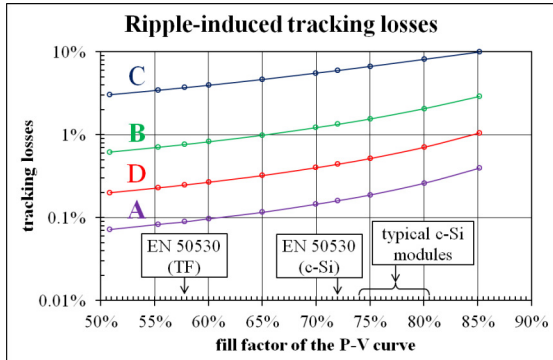


Figure 3: MPP tracking losses versus fill factor

Table III: Ripple-induced MPP tracking losses

| Fill factor | MPP tracking losses | | | |
|-------------|---------------------|-------|-------|-------|
| | A | B | C | D |
| 50.9% | 0.07% | 0.62% | 3.04% | 0.20% |
| 55.4% | 0.08% | 0.71% | 3.45% | 0.23% |
| 57.8% | 0.09% | 0.76% | 3.70% | 0.25% |
| 60.1% | 0.10% | 0.82% | 3.96% | 0.27% |
| 65.0% | 0.12% | 0.99% | 4.65% | 0.32% |
| 70.0% | 0.14% | 1.22% | 5.54% | 0.40% |
| 72.0% | 0.16% | 1.34% | 5.96% | 0.44% |
| 75.0% | 0.19% | 1.55% | 6.68% | 0.52% |
| 80.0% | 0.26% | 2.07% | 8.13% | 0.71% |
| 85.2% | 0.40% | 2.90% | 9.96% | 1.05% |

The simulated data represents a physical limit for the tracking efficiency. Even with a perfect MPP tracking algorithm, these values could not be exceeded in a real system.

Summary of the simulated data:

- The fill factor has a considerable impact on the MPP tracking performance. In a realistic design, the losses with a fill factor of 85% are more than twice as high as with the normative fill factor of 72%.
- The tracking losses of systems with thin film modules (fill factor 55...65%) are about 40% lower compared to systems with crystalline modules (fill factor 70...80%).
- The operating voltage has a very high influence on the MPP tracking losses. As can be seen by comparison of scenarios C and D, doubling the operating voltage can easily reduce the tracking losses by one decade.

To further investigate the influence of MPP power, capacitor size and operating voltage, a sensitivity analysis for these three parameters was made. For this, three simulations were performed. In each of them, one of the three parameters was variable while the other two were kept constant. The results are shown in Figures 4, 5 and 6.

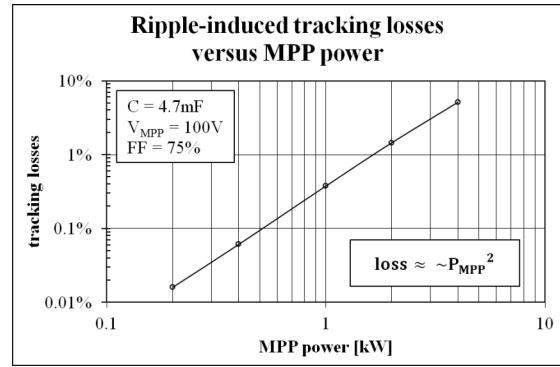


Figure 4: Effect of the MPP power

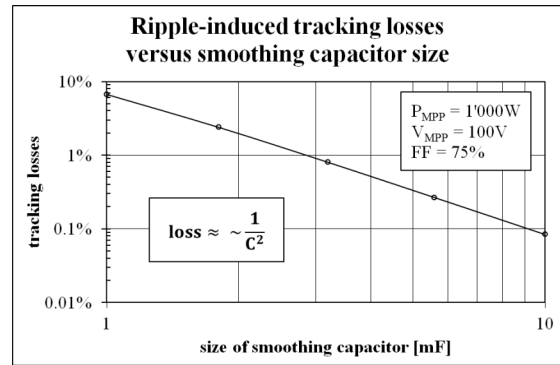


Figure 5: Effect of the smoothing capacitor size

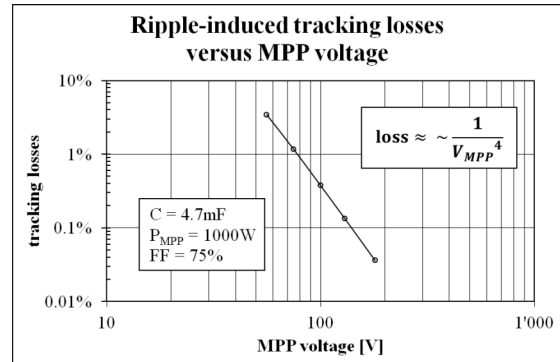


Figure 6: Effect of the MPP voltage

The following approximation rules can be deviated from the sensitivity analysis:

- The MPP tracking losses rise proportionally to the 2nd power of the MPP power.
- The MPP tracking losses fall proportionally to the 2nd power of the smoothing capacitor size.
- The MPP tracking losses fall proportionally to the 4th power of the MPP voltage.

These rules are a guideline only and allow a rough estimate of the tracking losses. When the tracking losses are higher than a few percent, these rules will become inaccurate. This is only a minor drawback because no reasonable design should have tracking losses that high.

Special care must be taken in low voltage systems. These will require a very large smoothing capacitor to keep the tracking losses low. On the other hand, if the inverter in use has a wide tracking voltage window (as most modern string inverters do), the ripple induced losses will be at maximum when the device is operating

at its minimum voltage. This is the reason, why the voltage of the string inverter in scenario A was chosen so low. If the same inverter operated at an MPP voltage of 500V, even with a fill factor of 85% the MPP tracking losses would be only about 0.01%.

6 MEASUREMENTS

This section contains some measurements to show that the ripple induced tracking losses are not only a theoretical problem. Figures 7 and 8 show an overlay of a measured P-V curve of a PV array simulator and the operating points of a very small inverter connected to this simulator. In both measurements, the open circuit voltage and the short circuit current of the P-V-Curve were identical. However, the curve in figure 7 is a normative curve with a fill factor of 72% where the curve in figure 8 has a fill factor of 80%.

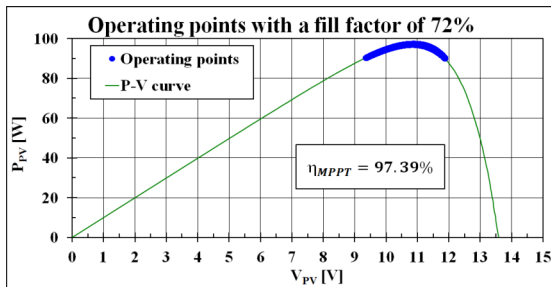


Figure 7: Measurements with a fill factor of 72%

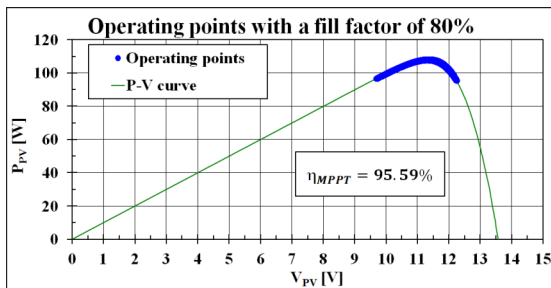


Figure 8: Measurements with a fill factor of 80%

In these figures the ripple is easy to see; the operating points are not permanent on the MPP, but are oscillating around the peak of the P-V curve. Because of this oscillation, in figure 7 the inverter has MPP tracking losses of 2.61%. This is already a severe loss. In figure 8 however, the fill factor and therefore also the MPP power and voltage are somewhat higher. Here, the tracking losses are already at 4.41%. This is more than the conversion losses of most modern PV inverters. Even if we assume a very high conversion efficiency of 98% for this inverter, the total efficiency [2] would only be about 93.7%.

Figure 9 shows a similar diagram, but in this case the device under test was a string inverter operating at approximately 50% of its rated power and at an MPP voltage of 420V. The ripple is very low, leading to an excellent MPP tracking efficiency of more than 99.9%. It must be pointed out that the distribution of the operating points is not only caused by the ripple, but also by the MPP tracking algorithm that is continuously adjusting the operating voltage in order to find the MPP.

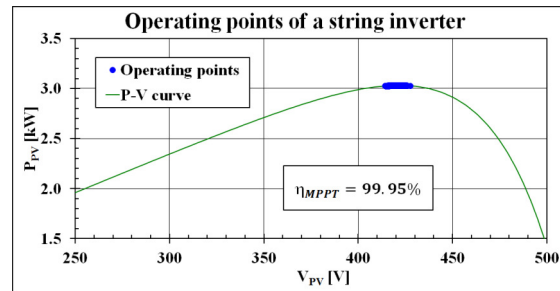


Figure 9: Measurements with a string inverter

7 CONCLUSIONS

This paper shows that the fill factor can have a considerable impact on the MPP tracking performance of single phase PV inverters. It also shows that the results of normative measurements can be too optimistic. The MPP tracking losses in a real application might be twice as high compared to the measurement results. When using string inverters with operating voltages of several hundred volts, the losses caused by the DC ripple are usually negligible. However, care must be taken in low voltage systems such as module inverters. Such devices need large smoothing capacitors to keep DC ripple and tracking losses small.

It can be assumed, that in the future the fill factor of PV modules will further rise. It is worth considering if the fill factor of normative test curves should be adapted to this development.

DISCLAIMER

Information contained in this paper is believed to be accurate. However, errors can never be completely excluded. Therefore any liability for correctness and completeness of the information or from any damage that might result from its use is formally disclaimed

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