New Procedure for Measuring Dynamic MPP-Tracking Efficiency at Grid-Connected PV Inverters

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ABSTRACT: At locations, where there are often variable cloudy conditions, besides the static also the dynamic MPPT-behaviour has to be considered. In the long-term monitoring projects performed by the PV laboratory of BFH-TI, it could be shown that dynamic MPP-tracking problems actually occur. In a paper presented at the 21st EU PV conference in 2006, first results of dynamic MPP-tracking tests carried out with quasi rectangular variations between two different power levels were presented [3]. Such tests can easily be realised with high measurement accuracy and give a good insight in the control behaviour of the inverter. More realistic are tests with ramps with rising and falling slopes of current (proportional to irradiance G) or MPP-power. It is more difficult to realise such tests with a high measuring accuracy. Like for static tests, before the start of a dynamic MPP-tracking test an initial set-up time is needed for stabilisation of the MPP-tracker in order to have a defined starting position. This stabilisation period is followed by a few test cycles during the actual measuring period TM. Inverters are always a little behind the effective MPP, therefore the offered MPP-power is not absorbed completely after a change. In this paper, these test patterns (according to the proposed new standard for inverter performance FprEN50530), results of many tests with them at different inverters and possible problems are discussed.

KEYWORDS: Inverter, MPP-tracking, dynamic behaviour

1 Introduction

In 2005 the new quantity overall or total efficiency ηtot was introduced, which can describe the static operating behaviour of a grid-connected PV inverter much better than conversion efficiency η alone [1]. Total efficiency ηtot is the product of DC-AC conversion efficiency η and static MPP-tracking efficiency ηMPPT. This quantity is increasingly used also by other institutions and professional journals (e.g. Photon). For such measurements suitable PV array simulators are needed [1], [4].

At locations, where there are often variable cloudy conditions, besides the static also the dynamic MPPT-behaviour has to be considered. Inverters with a fast MPP-tracker have a somewhat higher energy yield under quickly changing irradiance than devices with slow MPP-tracking (MPPT). In a study of FhG-ISE in 2005, it was shown that with a correct sizing of the inverter and a fast dynamic MPP-tracking, in principle a few additional percent of energy could be obtained from the same PV array [2]. In the long-term monitoring projects carried out by the PV laboratory of BFH-TI, it could be shown that dynamic MPP-tracking problems actually occur. In a paper presented at the 21st EU PV conference in 2006, first results of dynamic MPP-tracking tests carried out with quasi rectangular variations between two different power levels were presented [3]. Such tests can easily be realised with high measurement accuracy and give a good insight in the control behaviour of the inverter. More realistic are tests with ramps with rising and falling slopes of current (proportional to irradiance G) or MPP-power. It is more difficult to realise such tests with a high measuring accuracy. Like for static tests, before the start of a dynamic MPP-tracking test an initial set-up time is needed for stabilisation of the MPP-tracker in order to have a defined starting position. This stabilisation period is followed by a few test cycles during the actual measuring period TM. Inverters are always a little behind the effective MPP, therefore the offered MPP-power is not absorbed completely after a change.

2 Definition of Dynamic MPP-Tracking-Efficiency or -Accuracy

Dynamic MPP-tracking efficiency or MPP tracking accuracy ηMPPTdyn can be defined as:

\[ \eta_{MPPT_{dyn}} = \frac{\int_{0}^{T_M} v_{DC}(t) \cdot i_{DC}(t) \cdot dt}{\int_{0}^{T_M} p_{MPPT}(t) \cdot dt} \] (1)

where

- \(v_{DC}(t)\) = voltage at the DC input of the inverter.
- \(i_{DC}(t)\) = current at the DC input of the inverter.
- \(p_{MPPT}(t)\) = available maximum power of PV array simulator in the respective instantaneous MPP.
- \(T_M\) = Measurement duration (start at \(t = 0\)).

The integral in the denominator represents the whole MPP energy that could be absorbed under optimum conditions by the inverter.

In 2008, the PV laboratory of BFH-TI participated in a workgroup in Germany, which had to create a draft for a standard to measure overall efficiency of PV inverters including suitable test patterns with ramps for MPP-tracking. Many different test patterns were proposed and discussed. In order to get practical results of tests with these test patterns, several inverters from different manufacturers were tested in order to obtain optimum test patterns that are neither too stringent nor too mild. These test patterns were finally approved by the working group and are now included in the final draft for a provisional European standard (FprEN50530). In this paper, the resulting test patterns and some test results are shown.

1
3 Test Results

3.1 Dynamic MPPT Problems Registered in Real Operation

During the long-term monitoring projects of PV plants, which have been performed since 1992 by the PV laboratory of BFH-TI, some dynamic MPP tracking problems in real operation could be registered (see fig. 1).

This problem was caused by several ramp-like variations of irradiance that irritated the inverter. Between 14:00 and 14:35 the power $P_{DC}$ absorbed by the inverter is sometimes too low compared with the irradiance, as the DC voltage $V_{DC}$, on which it operates, has increased due to the irritation of the MPP-tracker and for some time is considerably higher than the MPP-voltage $V_{MPPT}$.

3.2 Possible Problems with Reproducibility already During Static MPPT Tests

It will be shown later that sometimes there are reproducibility problems with dynamic MPP-tracking tests.

In some cases there may be minor reproducibility problems already during static MPP-tracking tests. With some inverters, especially at low power levels in the range of a few percent of $P_{DCn}$, under static conditions minor MPPT-problems may occur, which are caused by the fact that from time to time the inverter looks for a possible new MPP not only in close vicinity of the actual MPP, but in a wider neighbourhood of it (see fig. 2) [4].

During the time where $P_{DC}$ is $< P_{MPPT}$, a certain amount of energy is lost, and thus the measured value of $\eta_{MPPT}$ is reduced somewhat. Depending on the duration of the measuring interval $T_M$ used to determine $\eta_{MPPT}$ (e.g. 1 to 10 minutes, see [1]) 0, 1 or 2 such search processes in the wider neighbourhood occur. Therefore, depending on the state of the internal clock in the inverter at the start of the measuring period and the duration of this measuring interval $T_M$, measured $\eta_{MPPT}$ may vary here between 93% and 99.9%, i.e. measurement of static $\eta_{MPPT}$ is not completely reproducible at this power level for such devices. This problem can be alleviated considerably by using a sufficiently high measuring interval $T_M$. The higher $T_M$, the closer the measured values of $\eta_{MPPT}$ are together and the better the reproducibility. Therefore in the final draft for a European standard FprEN 50530 for $T_M$ 10 minutes are proposed.

3.3 Definition and Description of the Different Test Ramps used for Dynamic MPPT Tests

In the workgroup in Germany, which was already mentioned, in course of 2008 different test patterns with ramps of different rise time were discussed and examined (see fig. 3 and 4). During these tests the number $n$ of repetitions and the time intervals $t_1$ … $t_4$ have to be varied in a wide range, in order to test if the MPP-tracking algorithm of the inverter can follow irradiance variations with different rise time without problems.

![Fig. 3: Test with variations between low and medium irradiance (10% to 50% of $G_{STC}$ = 1 kW/m², some variation of $V_{MPPT}$).](image)

![Fig. 4: Test with variations between medium and high irradiance (30% to 100% of $G_{STC}$ = 1 kW/m², low variation of $V_{MPPT}$).](image)
The individual tests are defined by the following description code (n×(t1/t2H/t3/t4L)), see table 1):

Number \( n \) repetitions, then \( x \) and in brackets the duration \( t_1 \) of the rise time in seconds, then the dwell time \( t_2 \) at high level in seconds (number + H), then the duration \( t_3 \) of the fall time in seconds and finally the dwell time at low level in seconds (number + L). According to the model for the I-V curve used in the PV array simulator, \( P_{\text{PMP}} \) is about proportional to irradiance \( G \), whereas \( V_{\text{MPP}} \) varies slightly according to irradiance \( G \). The measurements are relatively time consuming. For a measuring campaign according to table 1 including the set-up time of 300 s on the starting level for each test about 6½ hours are needed.

### Table 1: Planned ramp tests, number of repetitions and rise, dwell and fall times for irradiance or power variations for variation from low to medium (on top of table) and medium to high (on bottom of table) irradiance according to FprEN50350.

<table>
<thead>
<tr>
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<td>(600 / 10H / 400 / 10L)</td>
<td>1940</td>
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<tr>
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<td>(200 / 10H / 200 / 10L)</td>
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<td>Total</td>
<td>Time for Setup + Measurement</td>
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<tr>
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### 3.4 Results of Dynamic MPP Tests with such Ramps at Different Inverters

#### 3.4.1 Overview Diagrams

Test patterns with ramps according to table 1 were used to perform dynamic MPP tests at six different inverters (INV1 to INV6). The MPP tracking algorithm used by the manufacturer is decisive for the dynamic tracking behaviour. Especially useful were tests with two inverters (INV3 and INV6) from two different manufactures, for which an old firmware version with relatively poor dynamic MPP tracking behaviour and a new firmware version with very good dynamic MPP tracking behaviour were available.

Fig. 5, 6 and 7 show the results of such dynamic MPP tests at INV3 and INV6 with old firmware in overview diagrams indicating measured \( \eta_{\text{MPPTdyn}} \) for different ramp steepness. It is obvious that the devices with the old firmware have problems at certain ramp steepness and measured values of \( \eta_{\text{MPPTdyn}} \) are considerably below 100%.

![Fig. 5](image)

**Dynamic MPP tracking efficiency \( \eta_{\text{MPPTdyn}} \) for INV3**

\( \text{V}_{\text{MPPT}} = 295 \text{V} \); old firmware, test 1

**Fig. 5:** Results of a complete dynamic MPP-tracking test with ramps according to table 1 at the inverter INV3 with old firmware (test run 1). The measured values of \( \eta_{\text{MPPTdyn}} \) are all in the range between 96% to 100%, there is no pronounced "resonance", where the device is seriously irritated by the repeated ramps.

![Fig. 6](image)

**Dynamic MPP tracking efficiency \( \eta_{\text{MPPTdyn}} \) for INV3**

\( \text{V}_{\text{MPPT}} = 295 \text{V} \); old firmware, test 2

**Fig. 6:** Results of a complete dynamic MPP-tracking test with ramps according to table 1 at the inverter INV3 with old firmware (test run 2). Here for a slope of 20 W/m²/s some kind of "resonance" occurs, where the device is irritated by the repeated ramps (like in fig. 1) and therefore dynamic MPPT efficiency is reduced. A comparison with fig 5 reveals that there is no exact reproducibility here!
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Dynamic MPP tracking efficiency \( \eta_{\text{MPPTdyn}} \) for INV6

\( V_{\text{MPPThigh}} = 330 \text{V} \); old firmware

During identical tests the resulting values at a given ramp steepness may be somewhat different, i.e. the test results are not completely reproducible for inverters with deficiencies in dynamic MPP tracking.

Fig. 8, 9 and 10 show the results of similar tests with new firmware that was improved by the manufacturers in the meantime. The results of the tests are now excellent. Good reproducibility was observed with all devices tested so far with good results at such tests (compare e.g. fig. 8 and fig. 9).

Fig. 11, 12, 13 and 14 show the results of further tests with test ramps according to table 1 at other inverters with some deficiencies in dynamic MPP tracking and therefore also problems with reproducibility (compare at first fig. 11 and 12 and then fig. 13 and 14).
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3.4.2 Time Diagrams of Specific Dynamic Tests

In order to get a better understanding of the behaviour of inverters during dynamic MPP-tracking tests, it makes sense to create diagrams, in which the DC power $P_{DC}$ absorbed by the inverter and the operating voltage $V_{DC}$ are displayed versus time at a certain ramp steepness (see fig. 15 to 23). In some cases also older test patterns than those indicated in table 1 were used for such tests.

Fig. 15 to 20 show tests with INV3, IV4, INV5 and INV6 during which the MPP tracking algorithm is considerably disturbed.

Fig. 15: Time diagram of a ramp test according to table 1 with 2 W/m²/s at INV4 (10% $\Rightarrow$ 50%). $V_{DC}$ starts at the correct $V_{MPP}$, but then decreases more and more despite increasing $P_{DC}$. When $P_{DC}$ decreases $V_{DC}$ remains constant. Only when $P_{DC}$ increases the next time, $V_{DC}$ increases again, but afterwards during the next increase of $P_{DC}$ it goes again in the wrong direction. As already mentioned, during the development of the tests also other tests were carried out with ramps that are not contained in table 1 (see fig. 16, 17 and 18).

Fig. 16: Time diagram of a ramp test according with 40 W/m²/s and dwell time 5 s (instead of 10 s) at INV5 (10% $\Rightarrow$ 50%). During the test $V_{DC}$ decreases more and more and accordingly $P_{DC}$ also decreases more and more. Here $\eta_{MPPT dyn}$ is only 86.7%.

Fig. 17 shows a time diagram of INV3 with old firmware during such a test with a ramp starting at the high instead of the low level. Here the reason for the non reproducible behaviour of the MPP tracking algorithm used can be explained quite well (fig. 18). A ramp steepness of 10 W/m²/s seems to be quite critical. But during tests from low to high level according to fig. 5 and 6 a steepness of 20 W/m²/s seems to be more critical.
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Due to another position of the internal clock of the inverter at the beginning of the test ($V_{DC}$ has been decreased a little bit immediately before, see yellow line) now this time the device decreases $V_{DC}$ continuously during increasing $P_{DC}$. The MPP tracking algorithm now assumes that this increase of $P_{DC}$ is a consequence of the reduction of $V_{DC}$ and that it shall simply go on in this direction. As the power $P_{DC}$ does not decrease as fast during a runaway towards lower voltages compared to a runaway in the direction of $V_{OC}$ $\eta_{MPPTdyn}$ does not drop as low as in fig.17 and 18.

In fig. 21, 22 and 23 the results of some tests with INV3 and INV6 with new improved firmware are presented, where the dynamic MPP tracking is now very good.

![Fig. 21:](image)

**Fig. 21:**
Time diagram of a ramp test according to table 1 with 10 W/m²/s (10% ⇒ 50%) at INV6 with new firmware. $V_{DC}$ starts at $V_{MPP}$ of the low power level and then increases slowly towards $V_{MPP}$ of the higher level. The dynamic behaviour is now excellent and $\eta_{MPPTdyn}$ rises to the very good value of 99.7%.

![Fig. 22:](image)

**Fig. 22:**
Time diagram of a ramp test according to table 1 with 20 W/m²/s (10% ⇒ 50%) at inverter INV3 with new firmware (same test pattern as in fig. 19 and 20). $V_{DC}$ starts a little lower than $V_{MPP}$ of the low power level and then increases slowly towards $V_{MPP}$ of the higher level and follows very quickly the appropriate value of $V_{MPP}$. Here a very good value of $\eta_{MPPTdyn} = 99.6\%$ is obtained. For a more detailed explanation see fig. 23.

Here the MPP tracking algorithm takes into account that an increase or decrease of $P_{DC}$ can not only be the result of a previous variation of $V_{DC}$, but may also have other causes (variations in irradiance), from time to time makes also a search into the other direction and if necessary remains on the same $V_{DC}$. 

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### Fig. 18:
Expanded detail of fig. 17. As long as the power increases, the algorithm simply assumes, that this power increase is due to the previous change of $V_{DC}$ and therefore it continues to vary $V_{DC}$ in the same direction. The observation interval is about 5 s.

![Fig. 18](image)

**Fig. 18:**
Expanded detail of fig. 17. As long as the power $P_{DC}$ increases, the algorithm assumes, that this power increase is due to the previous change of $V_{DC}$ and therefore it continues to vary $V_{DC}$ in the same direction. The observation interval is about 5 s.

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### Fig. 19:
Time diagram of a ramp test according to table 1 with 20 W/m²/s (10% ⇒ 50%) at INV3 with old firmware.

![Fig. 19](image)

**Fig. 19:**
Time diagram of a ramp test according to table 1 with 20 W/m²/s (10% ⇒ 50%) at INV3 with old firmware. If $P_{DC}$ decreases or remains constant $V_{DC}$ remains constant, too. If $P_{DC}$ increases, $V_{DC}$ decreases (more detailed explanation in fig. 20).

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### Fig. 20:
Expanded detail of fig. 19. The same explanation as in fig. 18 can be used: As long as the power $P_{DC}$ increases, the algorithm assumes, that this power increase is due to the previous change of $V_{DC}$ and therefore it continues to vary $V_{DC}$ in the same direction, i.e. to decrease.

![Fig. 20](image)

**Fig. 20:**
Expanded detail of fig. 19. The same explanation as in fig. 18 can be used: As long as the power $P_{DC}$ increases, the algorithm assumes, that this power increase is due to the previous change of $V_{DC}$ and therefore it continues to vary $V_{DC}$ in the same direction, i.e. to decrease.
4. Conclusions

Many tests performed so far at different inverters have shown, that dynamic MPP tracking behaviour can be improved considerably by an intelligent control software without affecting static MPP tracking.

It could be demonstrated that at two inverters from different manufacturers by means of a mere improvement of the MPP tracking software without any changes at the inverter hardware very significant improvements of the dynamic MPPT behaviour were possible. Therefore every manufacturer should be able to implement analogue improvements without significant additional cost.

The test procedures presented here with ramps of different steepness are appropriate to determine the quality and speed of the dynamic MPP tracking of an inverter. Due to the many different steepness values used during the test it should be possible to discover possible problems at most inverters.

Somewhat disappointing is the fact, that at inverters with bad dynamic MPP tracking some problems exist in reproducing exactly the measured values of $\eta_{MPPT, dyn}$ at the different test patterns. It has been shown that this is a general problem, because the internal checks of MPP tracking in an inverter is always performed by means of a periodicity controlled by its internal clock. It is obvious that a synchronisation between the test equipment and this internal clock is not possible. However, during all tests performed so far reproducibility was very good at inverters with good dynamic MPP tracking.

In the draft standard mentioned (FprEN50530) also a turn-on / turn off test with a very slow variation of irradiance between 0.2% of GSTC and 10% of GSTC is described. Due to space limitations, in this paper the results of these tests are not discussed.

With the existing and successfully commissioned equipment now available at the PV laboratory of BFH-TI it is possible to perform similar dynamic MPPT tests at inverters between 100 W and 100 kW as a service to interested manufacturers.

Important Notice

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

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References:


Further information and many publications about the research activities of the PV laboratory of BFH-TI (former names: HTI or ISB) on the internet: http://www.pvtest.ch