Measurement of Dynamic MPP-Tracking Efficiency at Grid-Connected PV Inverters

H. Haeberlin, L. Borgna, M. Kaempfer and U. Zwahlen
Berne University of Applied Sciences (BFH), Engineering and Information Technology, Division of Electrical- and Communication Engineering, PV-Laboratory, Jlcoweg 1, CH-3400 Burgdorf, Switzerland
Phone: +41 34 426 6811, Fax: +41 34 426 6813, Mail: heinrich.haeberlin@bfh.ch, Internet: www.pvtest.ch

ABSTRACT: 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. In this contribution, a method and some measurements to determine dynamic MPP-tracking behaviour of grid-connected PV inverters is discussed and a first assessment of the different control strategies used is given.

KEYWORDS: Inverter, Grid-Connected, Dynamic Maximum Power Point Tracking.

1. Introduction

Last year at the 20th EU PV conference in Barcelona the new quantity „total efficiency η_{tot}" 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 η_{tot} is the product of DC-AC conversion efficiency η and static MPP-tracking efficiency η_{MPPT}. In an other contribution at this conference, measured curves for η_{tot} for many different inverter types at 3 different DC voltages are shown [2].

At locations, where there are often variable cloudy conditions, besides the static also the dynamic MPPT-behaviour has to be considered. 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 [3]. In this contribution, a method and some measurements to determine dynamic MPP-tracking behaviour of grid-connected PV inverters is discussed.

2. Measurements of static MPP-tracking efficiency η_{MPPT}

Static MPP-tracking efficiency or MPP-tracking accuracy η_{MPPT} can be determined as follows [1]:

$$\eta_{MPPT} = \frac{1}{P_{MPP} \cdot T_M} \int_0^{T_M} v_A(t) \cdot i_A(t) \cdot dt \qquad (1)$$

v_A (t) array voltage, i_A(t) array current at inverter input, T_M = duration of measurement (started at t = 0), P_{MPP} = available maximum PV power at MPP of the array.

As described in [1], after the selection of a new power level a certain stabilisation period is necessary, before a measurement of static MPP-tracking efficiency η_{MPPT} can start (e.g. 60s, for inverters with slow tracking also longer). Then, during the subsequent measuring period T_M (mostly 60s to 300s), DC voltage and DC current are sampled with high speed (e.g. 1000 to 10000 samples/s) at the very same moment.

3. Definition of dynamic MPP-tracking efficiency

For dynamic tests simulating days with variable cloudy conditions, relatively fast variations between two well defined power levels are useful. For small PV plants, the edges are steeper than for large PV plants. A test procedure that can be easily realised consists of nearly rectangular variations between about 20% and 100% of the rated values of current (or power) and only very few (1-3) intermediate stages that are reached only during a very short time (e.g. 100ms – 200ms).

For realistic dynamic MPPT-Tests it is essential that the MPP-voltage of the I-V-curves does not remain constant at the different power levels, but varies slightly like in a real PV array operating at constant cell temperature, i.e. it must decrease somewhat when the power is reduced.

Before a dynamic MPP-tracking test, like for static tests, the P_{MPP}-values of the different power levels to be used must be determined and a stabilisation period of 1 to 5 minutes has to be inserted. Then some test cycles (e.g. 3) follow, during which the desired MPPT-measurement takes place. Of course, most inverters do not find the actual MPP at once after a change, therefore the power offered is not absorbed completely in the beginning. Time T_{Mi}, during which the high and the low power level is offered, may vary between 2s and 60s, resulting in a cycle time of 4s to 120s and a total test time $T_M = \Sigma\, T_{Mi}$ of ≤ 6 minutes for a selected power and voltage level.

Dynamic MPPT-efficiency can then be defined as:

$$\eta_{MPPTdyn} = \frac{1}{\sum P_{MPPi} \cdot T_{Mi}} \int_0^{T_M} v_A(t) \cdot i_A(t) \cdot dt \qquad (2)$$

Total amount of energy offered during the test:

$$\Sigma\, P_{MPPi} \cdot T_{Mi} = P_{MPP1} \cdot T_{M1} + P_{MPP2} \cdot T_{M2} + ... + P_{MPPn} \cdot T_{Mn} \qquad (3)$$

Total measuring time:

$$T_M = \Sigma\, T_{Mi} = T_{M1} + T_{M2} + T_{M3} + ... + T_{Mn} \qquad (4)$$

Thus dynamic MPP-tracking efficiency is the ratio between the energy effectively absorbed by the inverter to the energy offered by the PV array simulator in the MPPs reached during the test cycle.

It was found that for some inverters the results obtained depend significantly on the starting conditions. If the power variations start from a low power level that was stable for a prolonged period (see fig. 1) the results were different from those obtained when the power variations start from a high power level maintained for some time before the beginning of the test (see fig. 2). Therefore two different test patterns make sense.

Before the test, the values of P_{MPP} at high and low power level are determined. Moreover, a initial stabilisation period of 5 minutes is offered to the inverter in order to give it the opportunity to find the actual MPP correctly. The dynamic test itself starts only with the fast variations between the low and the high level with 10 s per level.

The following test patterns were used for the tests:

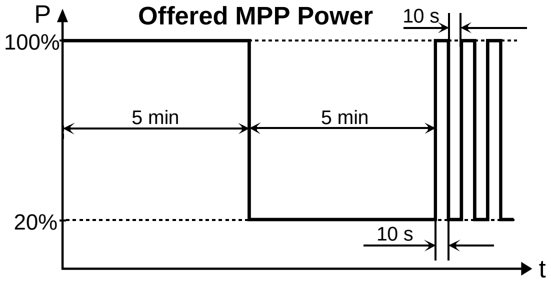

Fig. 1:
Power offered by the PV array simulator during a dynamic MPP-tracking test according to power profile 1 (L⇒H) proposed in this contribution.

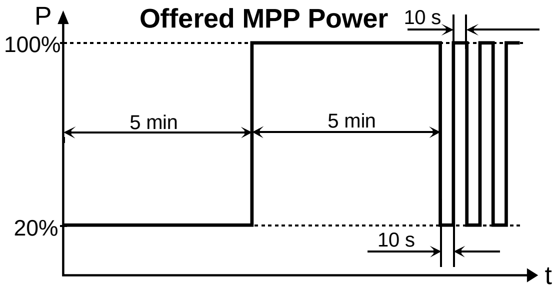

Fig. 2:
Power offered by the PV array simulator during a dynamic MPP-tracking test according to power profile 2 (H⇒L) proposed in this contribution.

4. Overview over test results

In fig. 3, 4 und 5 the exemplary dynamic tracking behaviour of an inverter is discussed. Due to space limitations, for the remaining inverters only one curve can be indicated.

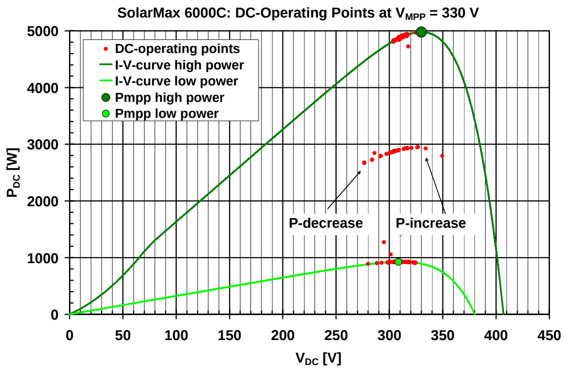

Fig. 3:
DC-operating points of the dynamic measurement according to fig. 4 at V_{MPP} = 330 V (at full power). Nearly during the whole test the device operates at the MPP-Voltage $V_{MPP\text{-}low}$ of the low power level, therefore left from the MPP and loses some power there.

In fig. 4 to fig. 12 the time dependency of the power $P_{DC}(t)$ absorbed by the inverter is shown, together with the power levels P_{MPP} high und P_{MPP} low. Moreover, referred to the second axis (at right), also the time dependency of the operating voltage $V_{DC}(t)$ with the corresponding voltage levels V_{MPP} high und V_{MPP} low at the MPP on the high and the low power level is indicated.

For realistic tests it is essential that V_{MPP} low is lower than V_{MPP} high, like with a real PV array at constant cell temperature.

On these diagrams you can see not only the instantaneous power absorption compared to the power offered by the PV array simulator, but also the reason why not the full offered power was absorbed.

Tests showed that with most inverters there is a relatively high dependency of the results obtained on the amount of DC voltage variation between the different power levels. Therefore a clear specification not only of the power levels, but also of the MPP-voltages used is essential for such measurements, otherwise reproducibility is not ensured.

In fig 3 and 4 you can recognise, that the inverter remains mainly on the old voltage V_{MPP} low corresponding to P_{MPP} low left from V_{MPP} high, therefore it is considerably left from the MPP when the offered power is P_{MPP} high and as a consequence, the device loses some power then.

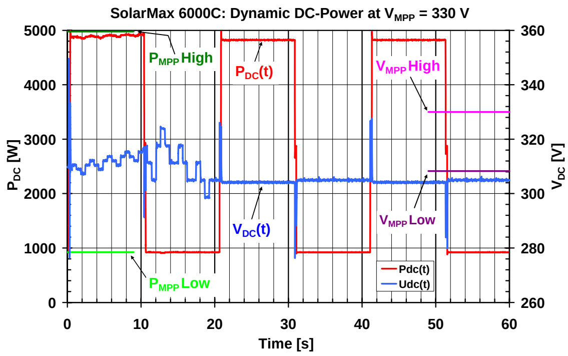

Fig. 4:
Dynamic DC power $P_{DC}(t)$ of a Solarmax 6000C at V_{MPP} = 330 V (at full power) and offered PV power according to fig. 1 (L⇒H). After a change from low to high, the power at the high level is not absorbed completely at once. Dynamic MPP-tracking efficiency calculated according to (2) is $\eta_{MPPTdyn}$ = 97.8%.

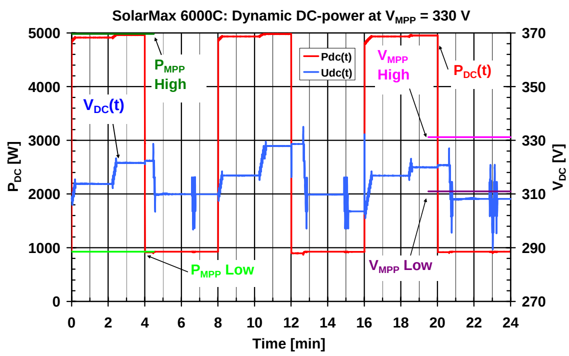

Fig. 5:
If after a change of the power level from a stable operating point more time is granted to the inverter, after some time it always finds the new MPP. After a change from low to high power, the device starts to seek the new MPP at once. After a change from high to low, however, the MPP-tracking starts only after a delay of 1 – 2 minutes. In this case, for slow changes of irradiance $\eta_{MPPTdyn}$ = 99.2%.

With this device, dynamic MPP-tracking efficiency is already pretty high.

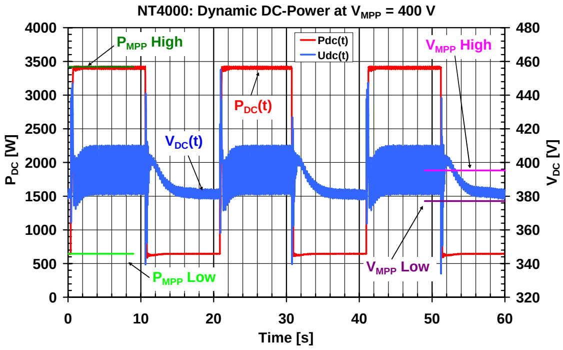

Fig. 6:
Dynamic DC power $P_{DC}(t)$ of a NT4000 at V_{MPP} = 400 V (at full power) and offered PV power according to fig. 1 (L⇒H). Dynamic behaviour of this device is excellent at this voltage. Dynamic MPP-tracking efficiency calculated according to (2) is $\eta_{MPPTdyn}$ = 99.4%.
At a comparable voltage (V_{MPP} = 420 V) a Solarmax 6000C has an even slightly better dynamic behaviour ($\eta_{MPPTdyn}$ = 99.8%).

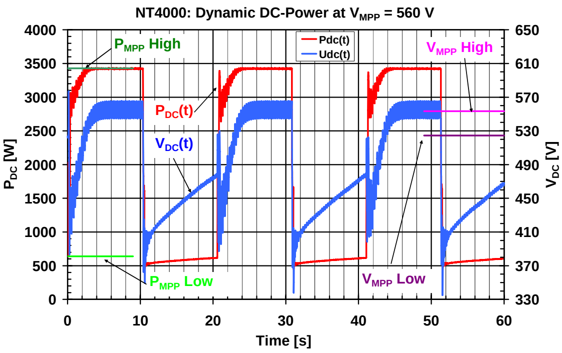

Fig. 7:
Dynamic DC power $P_{DC}(t)$ of a NT4000 at V_{MPP} = 560 V (at full power) and offered PV power according to fig. 1 (L⇒H). Dynamic tracking is fast in principle, but the performance of this device is not so good at this voltage, as it starts its search at 410 V. Dynamic MPP-tracking efficiency according to (2) is $\eta_{MPPTdyn}$ = 96.7% here.

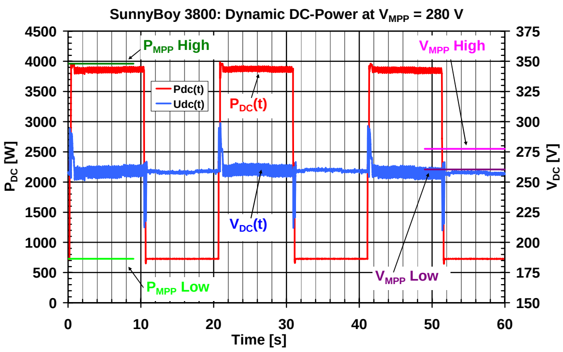

Fig. 8:
Dynamic DC power $P_{DC}(t)$ of a SB3800 at V_{MPP} = 280 V (at full power) and offered PV power according to fig. 1 (L⇒H). After a change of power, the rise and fall is quite fast, but the power at the high level is not absorbed completely at once, as the device remains at the old MPP-voltage V_{MPP}. Dynamic MPP-tracking efficiency calculated according to (2) is $\eta_{MPPTdyn}$ = 98.0%, therefore quite high.

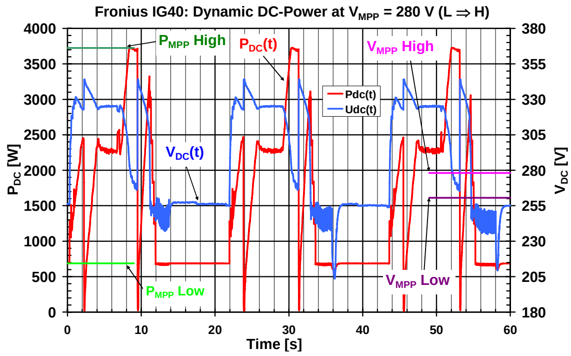

Fig. 9:
Dynamic DC power $P_{DC}(t)$ of an IG40 at V_{MPP} = 280 V (at full power) and offered PV power according to fig. 1 (L⇒H). After a change from low to high, the additional power offered is absorbed only gradually and with considerable delay. Probably this device has a problem with the activation of the second sub-inverter. It even stops for a short time. Dynamic MPP-tracking efficiency calculated according to (2) is $\eta_{MPPTdyn}$ = 68.9%. At other voltages the behaviour of this device is considerably better.

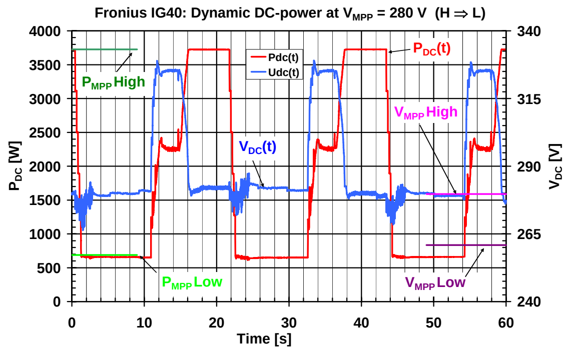

Fig. 10:
Dynamic DC power $P_{DC}(t)$ of an IG40 at V_{MPP} = 280 V (at full power) and offered PV power according to fig. 2 (H⇒L). The dynamic behaviour at the very same voltage and the very same variations is much better here. After a change from low to high, the additional power offered is still absorbed only gradually, but with less delay and no interruptions compared to fig. 9. Dynamic MPP-tracking efficiency according to (2) is $\eta_{MPPTdyn}$ = 89.7% here.

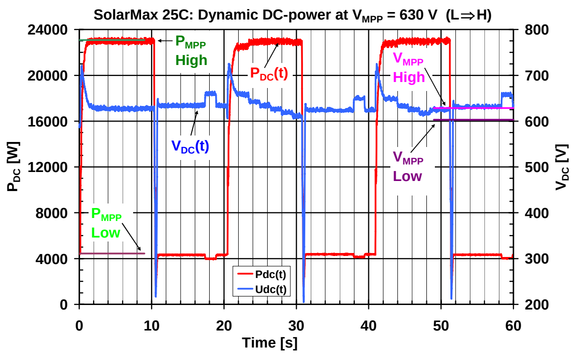

Fig. 11:
Dynamic DC power $P_{DC}(t)$ of a Solarmax 25C at V_{MPP} = 630 V (at nearly full power) and offered PV power according to fig. 1 (L⇒H). Dynamic MPP-tracking efficiency according to (2) is $\eta_{MPPTdyn}$ = 96.1% here. Due to the larger dimensions of the PV array, MPP-tracking of inverters for higher power may be somewhat slower without significant energy losses.

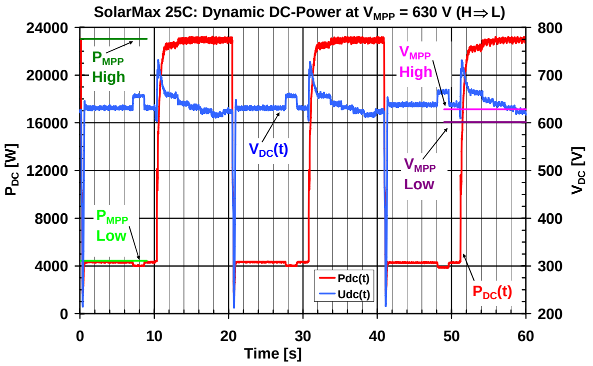

Fig. 12:
Dynamic DC power $P_{DC}(t)$ of a Solarmax 25C at $V_{MPP} = 630$ V (at nearly full power) and offered PV power according to fig. 2 (H⇒L). Dynamic MPP-tracking efficiency according to (2) is $\eta_{MPPTdyn} = 94.3\%$.

5. Discussion of test results

According to the test performed, many inverters try to remain on the average DC voltage on which they had been operating for the last minute (or so) before the variation. Therefore, upon a sudden change of power with minor voltage variation, they are already pretty close (within a few %) to the new MPP on the other power level. This seems to be a quite clever approach for the control algorithm. This family of inverters might be called "constant voltage" type (fig. 3-5, 8, 11, 12).

However, there are other types of inverters that rather try to remain on the same current or to exhibit about the same load R to the array (fig. 9 and 10). Therefore, if the offered array power increases, the voltage increases considerably and therefore for some time the operating point is far from the new MPP. They only find gradually the new MPP. If the recovery time is high, such inverters have a much lower dynamic MPP-tracking efficiency. If they share the load between two sub-inverters that are not always on, they may even turn off for a short time (see fig. 9). They are less disturbed if the power is reduced again. Such behaviour is certainly less efficient under varying cloudy conditions and can be easily found by means of the power-step test.

After a significant change of power, other inverters seem to start a completely new MPP search from their startup-voltage (see fig. 6 and 7, 410 V for this device). If the actual MPP voltage is close to this voltage, $\eta_{MPPTdyn}$ is high (fig. 6), if it is farther away a little lower (fig. 7).

By simple tests with step functions of power (with a defined voltage variation!), the ability of an inverter to follow fast irradiance changes measured by a dynamic efficiency figure under defined measuring conditions can be determined easily. Measurement of step responses is also a good and widely used means to examine and describe the dynamic behaviour of electrical circuits.

If a ramp is used with a few seconds between low and high power level as proposed in some other papers, nearly all inverters will easily pass such a test and the value of such a test for the user is very low. For small inverters, under cloud enhancement conditions, we have observed very sharp increases within a few 100 ms so far. Of course, for larger inverters in the order of a few 10 kW to a few 100 kW and more, due to the extension of the PV array the rise time can be reduced somewhat.

It is not intended to derive numerical values of additonal energy yield due to fast or energy losses due to slow dynamic MPP-tracking form such tests, because this would also depend from local weather conditions. However, it is clear that an inverter with fast dynamic response will behave better and have a higher yield at locations with fast changing irradiance conditions.

When we performed dynamic MPP-tracking tests, some-times we also measured the time required until the new MPP was found completely after a power change. In this case, we found that the time and therefore the dynamic MPPT efficiency was not always the same for the same device under identical conditions. We think that this de-pends on the internal clock of the inverters and that many inverters start a complete MPP-search only in some time intervals. Therefore, if you are unlucky, you have to wait some time (measured up to 2 minutes for some devices) until such a MPP-search starts again. With such inverters, dynamic MPP-tests may not be 100% reproducible.

6. Conclusions

Basic testing of dynamic MPP tracking with step functions should be quite easy to implement with PV array simulators with high stability and high-speed sampling of the DC-operating points of the inverter under test. To ensure reproducibility as much as possible, not only the variations of P_{MPP}, but also for V_{MPP} should be defined clearly.

Dynamic MPP-tracking efficiency determined with this method was already very good with many inverters.

More detailed reports (in German) are available under www.pvtest.ch > Wechselrichter-Testberichte.

Important Notice

Information contained in this paper is believed to be ac-curate. However, errors can never be completely exclu-ded. Therefore any liability in a legal sense for correct-ness and completeness of the information or from any da-mage that might result from its use is formally disclaimed.

Acknowledgements

Thanks go to all the institutions that gave financial support for this project. The work described in this paper was carried out in the project "PV system technology 2003-2006" under a contract with the Swiss Federal Office of Energy (BFE). Other parts of this project were co-funded by Localnet AG Burgdorf, GMS, c/o BKW, Bern and EBL, Liestal.

References:

[1] H. Haeberlin, L. Borgna, M. Kaempfer and U. Zwahlen: "Total Efficiency η_{tot} – a new Quantity for better Characterisation of Grid-Connected PV Inverters". Proc. 20th EU PV Conf., Barcelona 2005.

[2] H. Haeberlin, L. Borgna, M. Kaempfer and U. Zwahlen: "New Tests at Grid-Connected PV Inverters: Overview over Test Results and Measured Values of Total Efficiency η_{tot}".
Proc. 21th EU PV Conf., Dresden 2006.

[3] B. Burger: "Auslegung und Dimensionierung von Wechselrichtern für netzgekoppelte PV-Anlagen". 20. Symposium Photovoltaik, Staffelstein, 2005.

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