A new Approach for Semi-Automated Measurement of PV Inverters, especially MPP Tracking Efficiency, using a Linear PV Array Simulator with High Stability

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Abstract: HTI Burgdorf's PV laboratory has carried out many tests with small grid-connected PV-inverters since 1988. At first the size of the available PV generator was 3 kWp, then since 1994 60kWp. A significant extension of the testing facilities was possible with the introduction of suitable PV array simulators. Several linear PV generator simulators up to 25kW with high stability and fast transient response were developed in 1998 to 2000. In 2002 and 2003, a significant improvement of the measuring software was realised which makes possible semi-automated tests of PV inverters including the measurement of MPP-tracking efficiency. Only with such semi-automated tests it is possible to perform extended inverter tests under many different operating conditions (e.g. for different DC voltages and on I-V-curves with different fill-factors and shapes) in a reasonable time. Measurement of MPP-tracking efficiency is quite difficult and requires a PV array simulator of high stability and no interaction with the inverter to be tested. In this paper, a new method of extracting MPP-power directly from the measured data points is presented. In many cases, this method allows automatic determination of static and dynamic MPPT-efficiency with no need for time-consuming separate MPP-measurements on each power level with external devices.

KEYWORDS: Inverter - 1 : Performance - 2 : MPP-Tracking – 3 : PV array simulator – 4.

1. PC controlled linear PV array simulators 7.5 kW and 25 kW with high stability and fast response

In the PV laboratory of HTI, many inverter tests were carried out with and without PV array simulators. After a few years of problems with a commercial PV array simulator in the mid-90's, several models of own PV simulators were developed. At first diode chain simulators of up to 3 kW were used (similar to those which are in use in many test laboratories). However, such simulators have an inherent thermal stability problem and are limited to the fill factor of the diode chain used. Therefore other principal approaches were tested. In order to fulfil all essential requirements, the solution with a controlled linear current source proved to be best. In 2000 highly stable and fast PV array simulators of 7.5 kW and 25 kW (750V / 12 A and 40 A) with very good operational results were developed, which have the possibility to operate on I-V-curves with largely different fill factors. They have been used and continuously improved without problems since then. Despite the higher power losses for such PV array simulators, a linear design is more appropriate, because dynamic response is better and there are no internally generated HF voltages (no PWM switching frequency) which might compromise EMC measurements. Fig. 1 shows the principal block diagram of the realised 2 PV array simulators (one for 7.5 kW, the other for 25 kW).

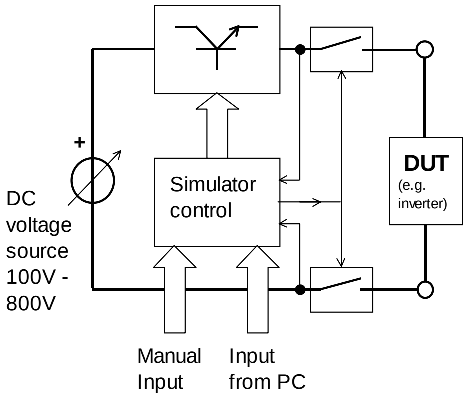

Fig. 1: Block diagram of the PV generator simulators developed at HTI's PV laboratory.

For safety reasons, when the simulator is not in operation, two series isolation switches at the output provide galvanic isolation. In order to keep power losses at the linear current source minimal, the DC voltage source has to be about 20V to 50V higher than the selected V_{OC}. Available maximum power is highest for I-V-curves with high fill factor (8 different curves available with analog I-V-curve generation, 16 with digital I-V-curve generation). The voltage source and the internal power electronics are floating to ground, all control signals are isolated by means of isolation amplifiers or opto-couplers.

Fig. 2: View of the PV generator simulator with $V_{OC} \leq 750V$, $I_{SC} \leq 40A$, $P_{MPP} \leq 25kW$.

Apart form the many advantages, there is one important drawback of the linear simulator design: If the simulator is operated close to the short circuit point with significantly high voltages of the voltage source feeding the circuit, quite a lot of power must be dissipated in the controlled current source. However, this is an unusual operating condition. The power dissipation can considerably be reduced by a suitable choice of the voltage of the feeding voltage source (only 20 V – 50 V higher than V_{OC} depending on the shape of the selected I-V curve) and an appropriate reduction of the current close to the short circuit point (fold-back current limitation for voltages > 300V across the current source stage). As inverters always start their operation at V_{OC} and then approach MPP and oscillate around it during operation, this behaviour does not affect inverter tests. Only switching parallel charge regulators shorting the PV generator would be affected, but they are hardly used for PV generators with V_{OC} voltages > 300 V.

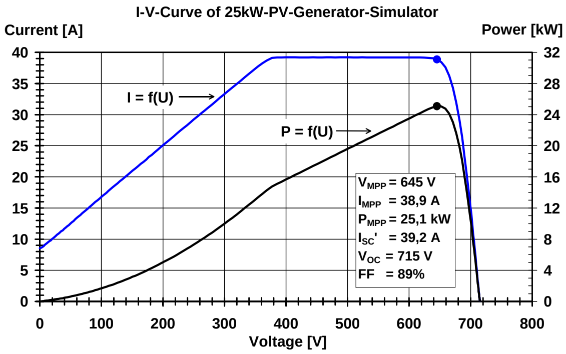

Fig. 3: I-V-curve (with fold-back current-limitation) of the highly stable 25kW PV-generator-simulator developed by HTI's PV laboratory.

2. Example of measuring results obtained with the PV array simulator: Inverter efficiency at different DC voltages

Many inverters have a wide input voltage range. It is obvious that DC-AC conversion efficiency also depends somewhat on the DC input voltage applied. Some results have already been published earlier (e.g. in [1]). While there are inverters where this dependency is relatively low, there are others with a relative high dependency on DC voltage. With the new semi-automated measuring software, such measurements can be performed in a reasonable time now.

Fig. 4 shows DC-AC conversion efficiency of an inverter with a relatively high voltage dependency. Power variation was performed by varying the current I of the simulator on a given I-V curve, therefore the voltage at lower power levels is somewhat lower. This is the best approach for simultaneous measurements of MPP-tracking efficiency, as measurements with a constant MPP-voltage would favour dumb inverters with poor MPP-tracking that sit only on the MPP-voltage found earlier.

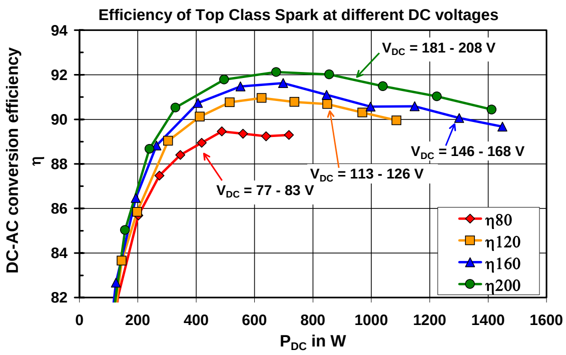

Fig. 4: DC-AC conversion efficiency of a Top Class Spark at different DC input voltages.

There are inverters that have a higher efficiency at higher voltages and others that have a higher efficiency at lower voltages. There are also inverters with a relatively narrow input voltage range that have already a measurable dependency of the efficiency on DC input voltage. Fig. 5 shows this dependency for a Top Class 4000 Grid II with such a relatively narrow input voltage range.

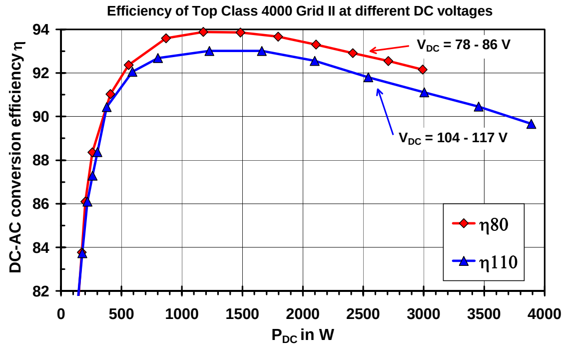

Fig. 5: DC-AC conversion efficiency of a Top Class 4000 Grid II at different DC input voltages.

3. Static MPP-tracking tests

For the static MPP-tracking tests performed at our PV laboratory, different steps of current on a fixed I-V-curve with a FF according to the desired cell technology (FF selectable from 50% to 85% in 5% steps) are used. V_{OC} is selected for the maximum I_{SC}. Power variation is performed by varying current I. This simulates irradiance variations with constant array temperature. As I is reduced, V_{MPP} is also reduced according to the I-V equation of the selected cell technology. Therefore the test clearly shows if the inverter under test is capable of tracking the MPP at different power levels by following V_{MPP}-variations. Before measurement of static MPP-tracking efficiency or MPP-tracking accuracy, a stabilization period of at least 60 seconds is reasonable. Then during a subsequent measuring period T_M, DC-current I and DC-voltage V is sampled simultaneously at a relatively high sampling rate (e.g. 1000 to 10000 samples per second) with subsequent averaging during 50ms or 100ms to reduce the number of data points and to eliminate the influence of the 100Hz ripple on the DC side of single phase inverters. Static MPP-tracking efficiency η_{MPPT} is the ratio between DC energy effectively absorbed during measuring period T_M divided by DC energy $P_{MPP}\cdot T_M$ offered to the inverter in T_M.

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

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

$v_A(t)$ array voltage, $i_A(t)$ array current at inverter input.
T_M = duration of measurement (started at t = 0).
Recommended: 60s to 300s per power level.
P_{MPP} = available maximum PV power at MPP of the array.

Conventional high precision power meters are usually too slow to determine MPP-values with sufficient accuracy, therefore the sampling and averaging method described proved to be much more significant and effective. The data points obtained can be displayed in a so called "cloud diagram" (see fig. 6 and 7).

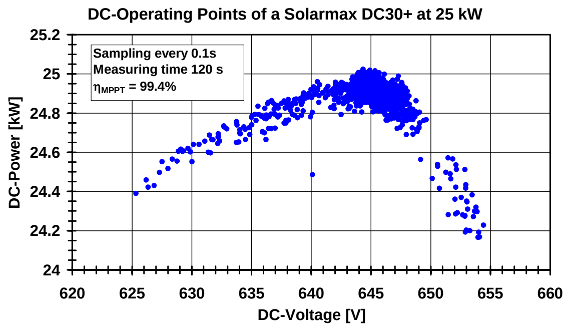

Fig. 6: Cloud diagram of an inverter Solarmax DC30+ operating at the I-V-curve of the PV simulator of fig. 3. Measured η_{MPPT} was 99.4%, MPP-tracking is very good.

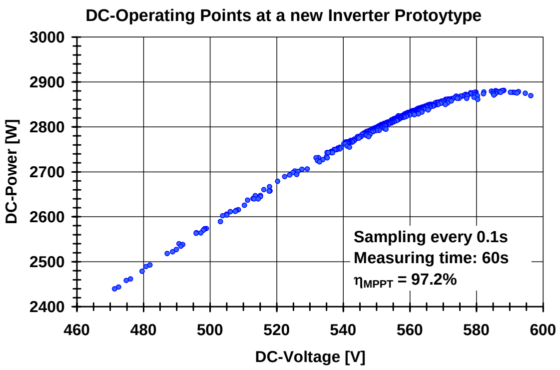

Fig. 7: Cloud diagram of a prototype of a new inverter. Measured η_{MPPT} was 97.2%, it is obvious that this device has a sporadic MPPT-problem.

Moreover, in many cases P_{MPP}-values can be determined by means of mathematical methods even without measuring MPP-power from the many data points obtained. This method, however, needs a certain time of constant P_{MPP} on a very stable I-V curve to get enough data points.

In a simplified model of a PV array, the power P = f(V) can be approximated by the following function:

$$P = a \cdot V - b \cdot V \cdot \exp(c \cdot V) \quad (2)$$

As a starting point for fitting with the least squares method, three points are taken: V_{OC}, the average value of 5% of all elements of the cloud with the highest values of V and the average value of 5% of all elements of the cloud with the lowest values of V. Thus the parameters obtained are already close to the desired final values and an optimisation with the least squares method considering all elements of the cloud can follow. This procedure keeps calculation time reasonably low. If the clouds contain the maximum, the error can be neglected. If the cloud is far away from the extrapolated P_{MPP}, there are some errors, but in this case η_{MPPT} is already pretty bad and it does not matter very much if it is a little higher or lower. An error estimation function is available for these cases. If a higher accuracy is desired, independent measurements (manual or automatic) with a separate I-V-curve measuring device are also possible. Examples of diagrams with extrapolated MPP are given in fig. 8 and 9.

From all measurements performed at different current/power levels on a given I-V-curve, a curve for measured $\eta_{MPPT} = f(P_{DC})$ can be obtained. Fig. 10 shows such a curve for a TOP Class 4000/6 Grid II. With some inverters, η_{MPPT} does not only depend on power and DC voltage, but also on the fill factor FF of the I-V-curve.

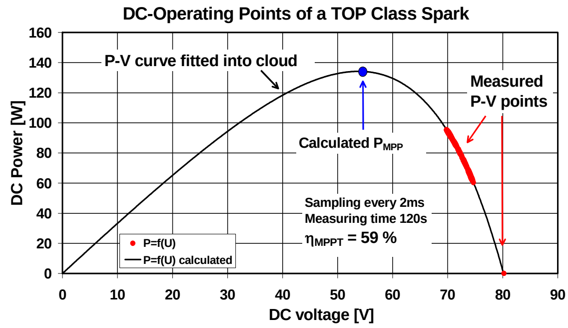

Fig. 8: Cloud diagram of a Top Class Spark (1.3 kW) and P-V-curve fitted into diagram using least squares fitting through cloud and V_{OC} to determine P_{MPP}. As V_{OC} of the simulated array is too low here, V_{MPP} is lower than the lower limit of the tracking window, therefore the MPP can not be found and measured η_{MPPT} is only 59 %.

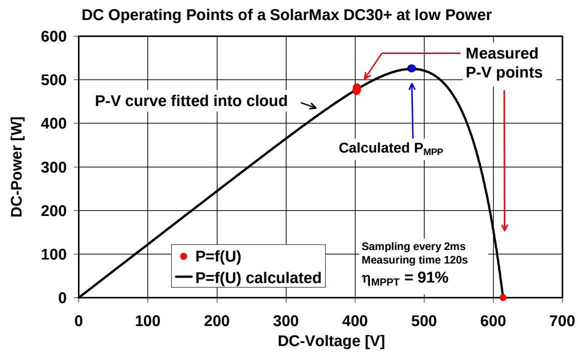

Fig. 9: Cloud diagram of a SolarMax DC30+ (30 kW) and P-V-curve fitted into diagram using least squares fitting through cloud and V_{OC} to determine P_{MPP}. At low power levels, the device operates at the minimum operating voltage of 400V. Therefore, if V_{MPP} is higher, η_{MPPT} must be lower, here only 91%. Loss of exact MPP-tracking at low power levels is typical for most inverters.

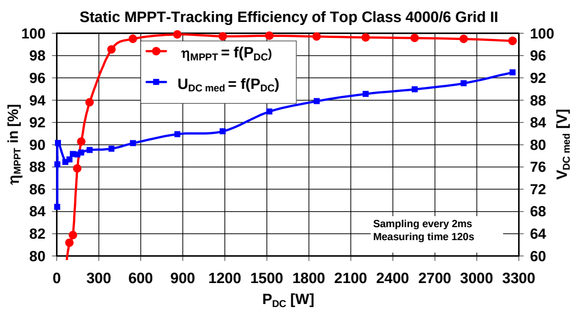

Fig. 10: Measured $\eta_{MPPT} = f(P_{DC})$ for a TOP Class 4000 Grid II operating on an I-V-curve with relatively low V_{OC}. Power is varied indirectly by varying the current I on a given I-V-characteristic of the PV array simulator. Besides η_{MPPT} also the average DC operating voltage V_{DC} is indicated in the same diagram. For DC-voltages lower than 80 V the inverter gets problems with MPP-tracking and therefore η_{MPPT} is lower there.

4. Dynamic MPP-tracking tests

For dynamic tests simulating cloudy days, relatively fast changes of current (or power) between only few (at least 2) different levels with known P_{MPP}-values are required. For small PV plants, ramps observed in practical arrays are steeper than in large PV arrays. In small systems up to a few kW, PV power may vary from 15% to 120% of rated power in less than 500ms under special weather conditions with sharply defined clouds (especially in spring and early summer). An inverter should at least not shut down under such conditions. In order to enable measurement of P_{MPP} with an independent device, a *limited number of current/power steps* is preferable. The optimum current/power rating is still to be discussed.

A good starting point is a nearly rectangular variation between about 10% and 100% of rated current/power with very steep ramps with only very few (1 – 3) intermediate power levels held during a very short time (e.g. during 100 ms to 200 ms). Before starting a dynamic MPP-test, a measurement of P_{MPP} on the planned power levels (like with the static test) must be carried out and a stabilization period of at least 60 seconds has to be provided. Then a few test cycles (e.g. 6) follow, during which the effective dynamic MPP-tracking test takes place. Of course, most inverters will not find the actual MPP at once, therefore the offered current or power is not absorbed by the inverter under test immediately after a change. The time T, during which the low and the high current level is maintained during a test cycle, may vary between 2s and 30s, resulting in a total cycle time between 4s and 60 s and a total duration $T_M = \Sigma\, T_{Mi}$ of a dynamic MPP-tracking test for the selected power and voltage level of less than 5 minutes.

Dynamic MPP-tracking efficiency or accuracy can then be calculated like in (1):

$$\eta_{MPPTdyn} = \frac{1}{\Sigma\, P_{MPPi} \cdot T_{Mi}} \int_0^{T_M} v_A(t) \cdot i_A(t)\,dt \qquad (3)$$

where

$$\Sigma\, P_{MPPi} \cdot T_{Mi} = P_{MPP1} \cdot T_{M1} + P_{MPP2} \cdot T_{M2} + \ldots + P_{MPPn} \cdot T_{Mn} \qquad (4)$$

(sum of different MPP-energies that could be absorbed under optimal conditions on different power levels)

T_{Mi} = time during which the PV array simulator offers MPP-power-level P_{MPPi}

$$T_M = \Sigma\, T_{Mi} = T_{M1} + T_{M2} + T_{M3} + \ldots + T_{Mn} \qquad (5)$$

Like static η_{MPPT} also dynamic MPP-tracking efficiency may depend also on the fill factor FF of the I-V-curve.

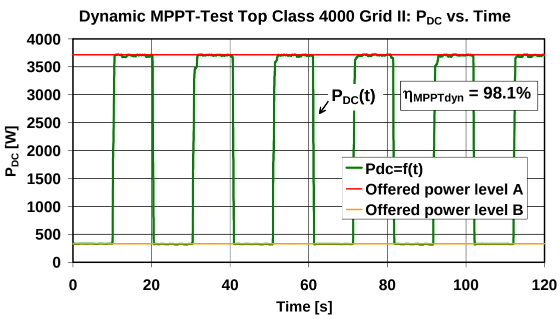

Fig. 11: Measured absorbed DC power $P_{DC}(t)$ of an inverter with a very good dynamic MPP-tracking. Measured $\eta_{MPPTdyn}$ is 98.1% according to (3), thus very high.

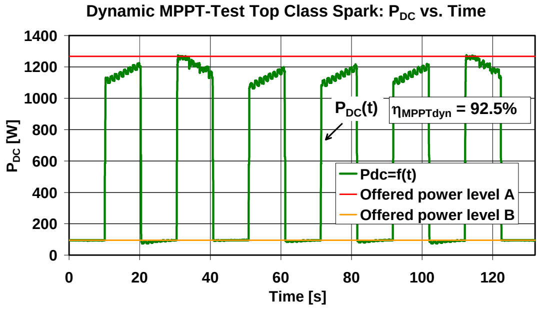

Fig. 12: Measured absorbed DC power $P_{DC}(t)$ of an inverter with an average dynamic MPP-Tracking behaviour. Measured $\eta_{MPPTdyn}$ is 92.5% according to (3).

5. Conclusions

With the measuring equipment and the control software described it should now be possible to examine static and dynamic MPP-tracking performance under reproducible conditions in the laboratory. Such tests will hopefully lead to a standard for MPP-tracking measurements that is not yet available due to lack of suitable test equipment in most laboratories**.**

The methods for measuring MPP-tracking efficencies (especially dynamic tracking efficiency) are not yet standardised. The methods described in this paper are a first approach, however, they are probably not yet the final solution. It would be interesting to exchange experience with other test laboratories that also measure static and dynamic MPP-tracking efficiency in order to develop further the measuring procedures.

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