New PV Array Simulator of 100 kW: Results of first Tests at a PV Inverter of 100 kW

H. Haeberlin, L. Borgna, D. Gfeller, M. Muenger and Ph. Schaerf
Berne University of Applied Sciences (BFH-TI), Division of Electrical- and Communication Engineering, Laboratory for Photovoltaics, Jcweg 1, CH-3400 Burgdorf, Switzerland
Phone: +41 34 426 68 11, Fax: +41 34 426 68 13, e-Mail: heinrich.haeberlin@bfh.ch, Internet: www.pvtest.ch

ABSTRACT: The PV laboratory of BFH-TI in Burgdorf has developed two linear PV generator simulators up to 25 kW with high stability and fast transient response between 2000 and 2004. With these devices, which are controlled by computers, it is possible to perform semi-automated tests of PV inverters including the measurement of MPP-tracking efficiency [3]. From these measurements, the total or overall efficiency can be calculated [4]. So far many inverter tests have been performed with this equipment (see www.pvtest.ch). As 100 kW is an important power limit in many countries, in a research project funded by the Swiss Federal Office of Energy, the PV laboratory was mandated to develop a corresponding PV array simulator of 100 kW (V_{OC} ≤ 810 V / I_{SC} ≤ 156 A). A first presentation of the state of this project was given at Valencia in 2008 [5]. In January 2009 this new PV array simulator was fully operational and it is now possible to perform automated tests under computer control (like those performed at low power devices) at much more powerful inverters up to 100 kW. In this paper, the results of first successful tests at a 100 kW-inverter Solarmax 100C are described.

KEYWORDS: PV array simulator, Inverter, MPP-Tracking, Overall efficiency

1 Introduction

The PV laboratory of BFH-TI has carried out many tests of grid-connected inverters in the power range between 100 W and 25 kW since 1988. For all inverters DC-AC conversion efficiency, harmonics of current, conducted electromagnetic interference (EMI) emissions, islanding after loss of line voltage, sensitivity to ripple control signals, turn-on power, range of operating voltage and operation on I-V-curves with offered MPP-power higher than rated power were tested. In the first years these tests were always carried out at real PV arrays, at first with up to 3 kWp, then with up to 60 kWp. Compared to the early nineties, DC-AC conversion efficiencies of grid-connected inverters have increased significantly in the last years [1]. Therefore for further optimisation of inverters other aspects become more interesting, e.g. how well an inverter can track the maximum power point of the array and therefore extract the maximum available power from the PV array (MPP-tracking efficiency). In [2] mostly theoretical concepts were discussed that were not confirmed by practical measurements. Because of the very high stability required, quantifiable MPP-tracking measurements are not possible with real PV arrays. For actual measurements of the MPP-tracking behaviour, more sophisticated laboratory equipment (computer controlled PV array simulators) and test procedures are necessary than for simple measurements of DC-AC conversion efficiency, if a sufficient accuracy and reproducible results must be obtained [3], [4], [5], [6]. By measuring DC-AC conversion efficiency η and MPP-tracking efficiency η_{MPP} at the same time, the new quantity “total efficiency η_{tot}” (or “overall efficiency”) can be determined, which allows a much better characterisation of an inverter [4], [5]. The higher the total efficiency, the more usable AC energy can be obtained from the energy offered by the PV array according to solar irradiation onto its surface and the higher the overall energy efficiency of the whole PV plant. Therefore it makes sense to optimize PV inverters for optimum total efficiency by means of measurements at suitable PV array simulators.

2 PV Array Simulators of BFH-TI’s PV laboratory

2.1 Old PV Array Simulators of up to 25 kW

The PV laboratory of BFH-TI in Burgdorf has developed two linear PV generator simulators of 20 kW and 25 kW with high stability and fast transient response between 2000 and 2004. With these devices, which are controlled by computers, it is possible to perform semi-automated tests of PV inverters including the measurement of MPP-tracking efficiency [3]. From these measurements, the total or overall efficiency can be calculated [4]. So far many inverter tests have been performed with this equipment at devices between 100 W and 25 kW [3], [4] (see www.pvtest.ch). During commissioning in fall 2008 it became clear that due to a somewhat too weak AC induction motor driving the smaller of the two DC generators used to power the PV array simulator, prolonged operation with an inverter load was possible only up to P_{APP} ≤ 92 kW. In January 2009 this motor was replaced by a stronger device and on January 20th, 2009 the first operation with an inverter with P_{APP} up to 101 kW was possible. After some further updates in the control software, completely automated tests with full rated power of P_{APP} = 100 kW were possible from spring 2009 on. For higher fill factors (≥ 80%) it can reach its rated performance (P_{APP} ≤ 100 kW, V_{OC} ≤ 810 V, I_{SC} ≤ 156 A). At present, this PV array simulator is probably the strongest device of its kind in the world.

2.2 New PV Array Simulator of 100 kW

As 100 kW is an important power limit in many countries, in a research project funded by the Swiss Federal Office of Energy, the PV laboratory was mandated to develop a corresponding PV array simulator of 100 kW (V_{OC} ≤ 810 V / I_{SC} ≤ 156 A). In January 2007, development of a large PV array simulator with these specifications was started. In July 2008, already I-V-curves with the full rated power P_{APP} = 100 kW could be measured [5]. However, during commissioning in fall 2008 it became clear that due to a somewhat too weak AC induction motor driving the smaller of the two DC generators used to power the PV array simulator, prolonged operation with an inverter load was possible only up to P_{APP} ≤ 92 kW. In January 2009 this motor was replaced by a stronger device and on January 20th, 2009 the first operation with an inverter with P_{APP} up to 101 kW was possible. After some further updates in the control software, completely automated tests with full rated power of P_{APP} = 100 kW were possible from spring 2009 on. For higher fill factors (≥ 80%) it can reach its rated performance (P_{APP} ≤ 100 kW, V_{OC} ≤ 810 V, I_{SC} ≤ 156 A). At present, this PV array simulator is probably the strongest device of its kind in the world.
With this device it is possible to perform detailed inverter tests for larger inverters up to this power level, which will also allow to determine their MPP-tracking behavior and total efficiency $\eta_{\text{tot}}$ as it is currently done for smaller devices.

Fig. 1 shows a front view of the device and fig. 2 a closer look to the front panel during operation. Fig. 3 shows an I-V-curve with a $P_{\text{MPP}}$ of 100.6 kW and fig. 4 an I-V-curve without current reduction at low voltages.

Fig. 1:
Front view of the new PC controllable PV array simulator with 100 kW (810V / 156A) developed at BFH-TI’s PV laboratory, using 156 elementary linear current sources with $I_{SC} \leq 1$A.

Fig. 2:
Closer look to the front panel of the new PC controllable PV array simulator with 100 kW while measuring the I-V-curve according to fig. 4.

Like with the 20 kW-simulator, in order not to overload the final stage, for I-V-curves with $V_{OC} > 250$V at high currents and low output voltages the current is reduced (fold-back current-limitation). As inverters mostly operate around the MPP, this self-protection feature of the simulator does not affect inverter tests.

In fig. 3, the I-V-curve from $V_{OC}$ down to a voltage of 550 V is identical to an I-V-curve with an $I_{SC}$ of 156A. However, the effective short circuit $I_{SC}$ current at $V = 0$ is only about 16 A, as $V_{OC}$ of the I-V-curve is 806 V, a relatively high value, which needs a considerable reduction of the current in order to remain in the safe operating area of the linear power MOS-FETs used.

For I-V-curves with lower $V_{OC}$ values, higher $I_{SC}$ values are possible. The lower $V_{OC}$, the higher the possible effective $I_{SC}$ at $V = 0$. Fig. 4 shows an I-V-curve with a $V_{OC}$ of 200 V and an $I_{SC}$ of 156 A.

To perform stable MPP-tracking measurements, the noise and stability of the I-V-curve is also an important issue. Measurement showed that for MPP-currents around 150 A the measured noise was below 50 mA peak, which is a very good value and will ensure a very high accuracy for MPP-tracking measurements.
Fig. 5 shows a test operation of the simulator with an inverter load of 100.9 kW and fig. 6 the expanded region around the MPP. Despite the strong magnification all operating points of the inverter are exactly on the P-V-curve measured before the test. Owing to the measuring principle used in the simulator, measuring accuracy of \( \eta_{\text{MPPT}} \) is better than 0.1% at rated power.

Fig. 5: Test operation of the 100 kW PV array simulator in January 2009. The inverter used as a load (Solarmax 100C) operates very close to the MPP. Measured MPP tracking (Solarmax 100C) operates very close to the MPP in January 2009. The inverter used as a load Test operation of the 100 kW PV array simulator Fig. 5: \( \eta \) principle used in the simulator, measuring accuracy of \( \eta_{\text{MPPT}} \) is better than 0.1% at rated power.

Fig. 5: Test operation of the 100 kW PV array simulator at three different voltages. PV array simulator 100 kW: Test operation at 101 kW with \( V_{\text{MPP}} = 680 \) V

Fig. 6: Region around the MPP (expanded) during the test operation of the 100 kW PV array simulator in January 2009 shown in fig. 5. All operating points of the inverter are exactly on the P-V-curve measured before the test. The MPP tracking algorithm of this inverter varies \( V_{\text{MPP}} \) in steps of a few volts from time to time.

Fig. 6: DC operating points of PV array simulator

3 Results of first Tests at a Grid-Connected PV Inverter of 100 kW

By the end of January 2009, with this PV array simulator semi-automated measurements of conversion efficiency \( \eta \), MPP-tracking efficiency \( \eta_{\text{MPPT}} \) and total or overall efficiency \( \eta_{\text{tot}} \) were performed at a 100 kW-inverter Solarmax 100C at MPP-voltages of \( V_{\text{MPP}} = 440 \) V, 560 V and 680 V up to \( P_{\text{MPP}} \leq 101 \) kW and \( I_{\text{MPP}} \leq 149 \) A (see fig. 7, 8 and 9). Due to the power limitation at about \( P_{\text{MPP}} = 101 \) kW and current limitation at about \( I_{\text{MPP}} \leq 149 \) A, rated power could not be reached completely during these tests. With linear extrapolation to full rated power \( P_{\text{DC}} \), also European efficiencies \( \eta_{\text{EU}} \), \( \eta_{\text{MPPT}} \) and \( \eta_{\text{tot}} \) were calculated (see table 1).

<table>
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<th>( V_{\text{MPP}} )</th>
<th>( \eta_{\text{EU}} )</th>
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<td>94.3%</td>
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<td>680V</td>
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Table 1: Measured static European efficiencies of a Solarmax 100C at different MPP-voltages \( V_{\text{MPP}} \) (values calculated with extrapolation to full rated power).

3.1 DC-AC-Conversion Efficiency

Fig. 7 shows the measured conversion efficiency of the inverter Solarmax 100C. The measured curves do not depend very much on the DC voltage. The conversion efficiency is somewhat higher at lower voltages. Owing to the power limitation at about \( P_{\text{MPP}} = 101 \) kW, rated power could not be reached completely during this test.

Fig. 7: Measured conversion efficiencies \( \eta \) of an inverter Solarmax 100C (100 kW) operating at the PV array simulator at three different DC voltages.

3.2 MPP-Tracking Efficiency \( \eta_{\text{MPPT}} \)

For optimum use of the solar energy that the PV array can produce, also a very good maximum power tracking is essential. In fig. 8 the measured values for static MPP-tracking efficiency \( \eta_{\text{MPPT}} \) are indicated. Compared to fig. 7, the curves are somewhat expanded. In general static MPP tracking is very good.

Fig. 8: Measured MPP tracking efficiencies \( \eta_{\text{MPPT}} \) of an inverter Solarmax 100C (100 kW) operating at the PV array simulator at three different voltages.

Like with many other devices, at low power levels in the range of a few percent of \( P_{\text{DC}} \), under static conditions minor MPPT-problems occur, which are caused by the fact that the inverter starts to look for a possible new
MPP not only in close vicinity of the actual MPP, but in a wider neighbourhood of it (see fig. 9). During the time where PDC < PMPP, a certain amount of energy is lost, and thus the measured value of ηMPPT is reduced somewhat. Depending on the duration of the measuring interval TM used to determine ηMPPT, (e.g. 1 to 10 minutes, see [4]) 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 TM, measured ηMPPT may vary here between 93% and 99.9%. i.e. measurement of static ηMPPT is not completely reproducible at this power level for such devices. This problem can be alleviated considerably by using a sufficiently high measuring interval TM. The higher TM, the closer the measured values of ηMPPT are together and the better the reproducibility. Therefore in the final draft for a European standard FprEN50530 for TM 10 minutes are proposed [11].

### 3.3 Total or Overall Efficiency ηtot

Due to the good static MPP tracking, total efficiencies ηtot do not differ very much from conversion efficiencies η, i.e. fig. 10 looks very similar to fig. 7.

![Fig. 9: P_DC and V_DC versus time during operation of the inverter at P_DC = 2.65 kW. About every 6 minutes the inverter looks for a possible new MPP not only in close vicinity of the actual MPP, but in a wider neighbourhood of it. Depending on the start and duration of the measuring interval TM, measured ηMPPT may vary here between 93% and 99.9%.

![Fig. 10: Measured overall or total efficiencies ηtot of an inverter SolarMax 100C (100 kW) operating at the PV array simulator at three different voltages. Due to the good static MPP tracking, total efficiencies ηtot do not differ very much from conversion efficiencies η, the figure looks similar to fig. 7.](image)

### 3.4 Harmonics of current

Harmonic of currents injected into grid by the Solarmax 100C is far below the limits in EN61000-3-12, which are mandatory only for inverters with AC currents up to 75 A, whereas rated AC current of this inverter is about 145 A. Also the total harmonic distortion THD of 1.7% and the partial weighted partial harmonic PWHD distortion of 0.9% are far below the limits of this standard (13% for THD, 22% for PWHD). Therefore harmonics of current produced by a Solaram 100C should not cause any problems in practical operation.

![Fig. 11: Harmonics of current of a Solarmax 100C operating with an AC power of about 95 kW at phase conductors L1, L2, L3 and limits of EN61000-3-12.](image)

### 3.5 Radio Frequency Interference (RFI)

On AC side, RF voltage produced by a Solarmax 100C at a commercial line-impedance stabilisation network (LISN) with 50Ω were somewhat higher than the limits for residential applications according to EN61000-6-3 or EN55011, but lower than the limits for industrial environments according to EN61000-6-4 or EN55011. As such a powerful device will often be used in industrial or free-field applications, this behaviour should be sufficient in most cases. If necessary, for special applications some additional filtering with a suitable line filter can be used.

![Fig. 12: RF disturbance voltages on the AC side produced by a Solarmax 100C operating with an AC power P_AC ≈ 80 kW measured at a commercial AC LISN with Z = 50 Ω. If this device is operated in industrial environments, no problems should occur, as the emissions are lower than the applicable standard. The more stringent limits for residential environments are trespassed somewhat between 3 MHz and 6 MHz.](image)
On the DC side, RF voltages measured at a DC-LISN with 150 Ω (for up to 1000 V and 150 A) were far below applicable standards, a very good result for such a powerful device (see fig. 12, schematic for such a LISN in [9]). As PV arrays may act as antennas for certain frequencies, sufficiently low RF emissions on the DC side are necessary not only for applications on large buildings, but also for free field applications.

3.6 Islanding

An attempt was also made to test the islanding behaviour of the inverter according to VDE126-1-1. Due to the limited power rating of the components available for the test, only a resonant circuit with a maximum reactive power of 12 kVar could be realised. Therefore the test could be carried out only at a maximum of 50 kW. Q = 2 according to VDE126-1-1. With the resonant circuit with reactive power of 8.3 kVar and a matched load of 8.3 kW at phase L1 (resulting in P1 < 50W and Q1 < 90Var) and interrupting only phase L1 (L2 and L3 still directly connected to line), a run-on time < 140 ms was registered. Further details (e.g. detailed schematic used) are available in [11].

Such ripple control signals are used by many utilities in Europe to interrupt heavy (and not essential) loads during critical peak load conditions in the grid (e.g. around noon).

Due to the limited power of the AC source used for the test, unfortunately it could only be carried out at about 12 kW. Fig 13 clearly shows that even at the highest voltage levels (up to 20 V RMS on all test frequencies) no interruptions occurred and that the device has a very high immunity against such signals.

4. Conclusions

In this contribution, for the first time results of extended laboratory tests (including precise MPP-tracking tests) of an inverter in the 100 kW-class can be presented. The general static behaviour of the SolarMax 100C proved to be very good, emissions of current harmonics were very low, RF emissions on the DC side were also very low and on the AC side in a range that can be accepted in many cases. The sensitivity to ripple control was also very low. More detailed results (in German) about the tests with SolarMax 100C can be found under www.pvtest.ch > publications [11].

At present, the PV array simulator of the PV laboratory of BFH-TI is probably the most powerful device of its kind in the world with such a high stability and measuring accuracy. It is also possible to perform automated tests and dynamic MPP-tracking tests with ramps according to the new FprEN50530. The results of inverter tests according to FprEN50530 are presented in a separate paper [7].

With the existing and successfully commissioned equipment available at the PV laboratory of BFH-TI it will be possible to perform similar tests at inverters up to 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