Evolution of Inverters for Grid connected PV-Systems from 1989 to 2000

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ABSTRACT: HTA Burgdorf’s PV laboratory has carried out many tests with small grid-connected PV-inverters since 1989. In spring 1994, a new test centre for PV-systems with a PV generator of 60 kWp became operational. With this test centre, tests of medium sized inverters up to 30kW are also possible. A significant extension of the testing facilities was possible with the introduction of solar generator simulators. Several PV generator simulators up to 25kW with high stability were developed in 1998 to 2000 (one of them computer controlled). With these simulators, partly automatic inverter tests can now be carried out much faster.

In this paper at first a short overview of the concepts used in grid connected PV inverters is given. Then the most important test results of all inverters tested (more than 28) will be displayed, which clearly shows the considerable progress achieved in the last years. The evolution of different important properties of PV inverters will also be discussed. Results of intense tests of some recently developed inverters used in many grid connected PV-systems will be used to illustrate some interesting cases or typical performance of new inverters. Reliability of inverters will considered using monitoring data of more than 45 PV plants continuously monitored since 1992.

Keywords: Inverter - 1: Grid-Connected - 2: Reliability – 3

1. EVOLUTION OF INVERTER CONCEPTS

In the first years only central inverters with a rated power > 1 kW were manufactured, that needed an extended DC wiring consisting of several strings in parallel (each string with several modules in series, see fig. 1).

Soon also self commutated three-phase inverters with pulse width modulation appeared on the market.

In order to reduce the expense and the safety problems caused by the extended DC wiring, after a few years string inverters were introduced, that were designed for a single string of several modules in series. Soon afterwards module inverters appeared, which were designed only for a single (medium or large sized) module, thus eliminating completely the DC wiring (see fig. 4).

![PV plant with central inverter](image1)

Three phase inverters often were grid-commutated and used thyristors. Smaller single phase inverters were often designed according to the concept of SI-3000 (self-commutated devices with galvanic separation by a HF transformer). This concept needed quite a number of components (see fig. 2), thus reliability of these early inverters was often insufficient. Therefore newer designs used again low frequency (LF) transformers (see fig. 3).

A key issue in all inverter designs was always DC-AC conversion efficiency \( \eta \). An important source for inverter losses is the transformer. By omission of the transformer, under the same conditions an efficiency increase around 2 % is possible. About 1995 new inverters without transformer appeared on the market (see fig. 5).

![PV inverter with LF transformer (e.g. TCG 3000)](image2)

![PV inverter with HF transformer (e.g. SI-3000)](image3)

![PV inverter with string inverters](image4)

![PV inverter with module inverters](image5)
## 2. Main Test Results

| Type               | Year of test | S
<table>
<thead>
<tr>
<th></th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>[kVA]</td>
<td>[V]</td>
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<tr>
<td>SI-3000</td>
<td>89</td>
<td>3.0</td>
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<tr>
<td>SOLCON 90/91</td>
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<td>3.3</td>
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<tr>
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<tr>
<td>SolarMax20 *</td>
<td>95</td>
<td>20</td>
</tr>
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<td>2.2</td>
</tr>
<tr>
<td>TCG II 2500/6</td>
<td>95</td>
<td>2.2</td>
</tr>
<tr>
<td>TCG II 4000/6</td>
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<tr>
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<tr>
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<tr>
<td>TCG III 4000</td>
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<tr>
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<tr>
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<tr>
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<td>99/00</td>
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<tr>
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<td>1.8</td>
</tr>
<tr>
<td>Convert 4000</td>
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<tr>
<td>SWR1500</td>
<td>99/00</td>
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</tr>
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</table>

### Key Specifications and Main Test Results

<table>
<thead>
<tr>
<th>Transformer</th>
<th>Harmonics of current</th>
<th>EMC AC</th>
<th>EMC DC</th>
<th>Sensitivity to telecontrol signals</th>
<th>Islanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro-Power transformer</td>
<td>European efficiency ( \eta_{EU} ) was calculated with the following formula (index value = percent of rated load): ( \eta_{EU} = 0.03 \eta_5 + 0.06 \eta_{10} + 0.13 \eta_{20} + 0.1 \eta_{30} + 0.48 \eta_{50} + 0.2 \eta_{100} )</td>
<td></td>
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### Key Performance Indicators

- **SI** = 3000 / 30V DC
- **VDC** = (typ.)
- **Harm. of current** = (0.1-2kHz)
- **EMC AC**
- **EMC DC**
- **Sensit. to telecontrol signals**
- **Islanding**

### Ratings

- **++** very good, meets the standard easily
- **+** good, meets the standard
- **0** satisfactory, meets the standard nearly
- **-** insufficient, does not meet the standard
- **- -** bad, does not meet the standard at all
- **n.t.** not tested

HF = high frequency, LF = low frequency (50Hz)

**Table 1:** Key specifications and main test results of the inverters tested by HTA Burgdorf from 1989 to 2001.

1) after modification by HTA Burgdorf
2) with optional DC-choke
3) with new control software
4) sufficient for module inverters (PV array small)
5) with 3-phase connection only
6) without galvanic separation DC-AC
7) new, improved model
8) slightly higher than limits for f < 300kHz
Table 1 shows the most important specifications and the main test results of the inverters tested in 1989 till spring 2001. The measuring concept, the test site used and some results of earlier tests are described in [2, 3, 4, 5].

2.1 Efficiency
Whereas in 1988 to 1990 European efficiency \( \eta_{EU} \) for inverters from 1.5 kW to 3.3 kW was in the order of 85.5 - 90%, it increased in the mid-nineties to 90 - 92% for inverters with galvanic separation DC-AC. Inverters of this size without galvanic separation now have reached values in the range 92.5 – 94.5%. With many inverters efficiency is somewhat voltage dependent (see fig. 6 and 7).

2.2 Harmonics of Current
Except EGR10 all inverters tested were self-commutated with HF pulse-width-modulation (PWM). Therefore harmonics of current are mostly below applicable standards (EN61000-3-2 or IEC1000-3-4). Therefore in practical operation no problems with harmonics should occur, unless line impedance is unusually high.

When many string- or module inverters are connected in parallel, due to the relatively low power of a single device, the observance of EN61000-3-2 by each inverter alone is not sufficient to avoid problems with harmonics. In this case, the whole plant (or significant parts of it) should observe the limits of the relevant standards.

2.3 Islanding
After loss of line voltage the first designs of inverters often had is islanding problems under matched load conditions. Newer inverters (with or without ENS for continuous line impedance monitoring) usually have no islanding problems when tested according to the relevant standards in Switzerland and Germany. However, there is no internationally accepted standard procedure for islanding tests yet.

2.4 Interruption of Line Connection under load
After an interruption on the connection to the mains, a SWR700 can generate an output voltage of up to 760 V peak or more than 2.3 times rated voltage (see fig. 8). If small loads are connected in parallel, they may be destroyed by such overvoltages. With SWR1500, a newer device from the same manufacturer, this effect is less pronounced.

Also other inverters from different manufacturers have shown the same behaviour, however with less peak voltages (up to 400 V peak). There were also inverters where such a interruption under load could even cause hardware defects under unfavourable conditions.

2.5 Sensitivity to Telecontrol Signals on the Line
With some of the first inverter designs (e.g. SI-3000 and SOLCON), hardware defects could occur under unfavourable conditions by low frequency telecontrol signals (e.g. 317 Hz) super imposed on the line. As sensitivity to telecontrol signals depends on voltage and frequency of the signal as well as on line voltage, a telecontrol signal simulator was developed in 1991. With this device, all inverters were subjected to simulated telecontrol signals. Although quite high voltages (up to 18V) were used, no hardware defects occurred. Most inverters did not show malfunctions, too. Especially German inverters with ENS sometimes switched off for some time after a strong telecontrol signal, but resumed normal operation afterwards. Thus telecontrol signals should not cause any problems with new inverters.

2.6 Electromagnetic Compatibility (EMC)
In 1989 – 1992 many inverters had very high RF emissions both on AC and DC side (up to 55dBuV above applicable limits!). At first inverter manufacturers realised, that usual RF voltage limits on the AC side (e.g. in EN 55014 or EN 50081-1) must be observed. Table 1 shows that after 1994/1995 the test results on the AC side in the original state (without modification) have improved considerably. Due to the relatively high PWM frequencies used, some manufacturers still have problems for frequencies below 300 to 500 kHz. Due to the relatively large extensions of the DC wiring in medium to large sized PV systems, which may act as an antenna, RF emissions must be limited also on the DC side. A first approach was the use of the RF limits for “other connections” contained in EN55014. In two different EU projects carried out in 1998 to 2001, the problem of RF-emissions on the DC side and appropriate measurement methods and limits to be applied have been examined thoroughly.
For frequencies >500 kHz somewhat lower limits than those in EN55014 are proposed. For modern inverters from experienced manufacturers these DC limits are no problem at all (example see fig. 10). Two contributions [6, 7] discuss this problem more in depth. Sufficient RFI filtering is also very useful to increase reliability of the inverters, as it enhances immunity against voltage transients that may cause inverter failures, a fact that many (especially new) manufacturers do not realise yet.

2.7 Maximum Power Point Tracking (MPPT)
Sporadic MPPT-problems often occur in the first designs from new manufacturers. Apart from obvious cases, they are relatively hard to detect and very sophisticated equipment (highly stable PV generator simulators) are needed to perform such tests.

2.7.1 PV Generator Simulators used at HTA Burgdorf
In 1995, a commercial PV simulator of 10 kW was purchased and first attempts to measure MPPT-behaviour of some inverters were made. However, this device was rather unreliable and its stability was by far not sufficient. Therefore own PV generator simulators (with high stability) were developed. The most powerful device is designed for P_{MPP} ≤ 25 kW, I_{SC} ≤ 40 A and V_{OC} ≤ 750 V. Fig. 11 shows an I-V curve, when the simulator is operating at rated power. Owing to the linear control scheme used, dynamic and EMC behaviour is excellent. In order not to overload the final stage, for I-V curves with V_{OC} > 350V for high currents and low output voltages the output current is reduced (fold-back current limit). As inverters usually operate around the MPP, this property does not affect inverter tests.

2.7.2 Measurement of MPP Tracking Efficiency
Static MPPT tracking efficiency can be defined as:

$$\eta_{MPPT} = \frac{1}{P_{MPP}} \int_{0}^{T_{M}} u_{a}(t) i_{a}(t) \, dt$$

where:
- $u_{a}(t)$ array voltage vs. time at inverter input
- $i_{a}(t)$ array current vs. time at inverter input
- $T_{M}$ = duration of measurement (started at $t = 0$)
- $P_{MPP}$ = available maximum PV power at MPP of the array

Quality of MPP-tracking of an inverter can be assessed by the following procedure: During a certain time all DC operating points of the inverters are sampled in a given time distance. These sampled operating points can be displayed in a “cloud diagram”. If the inverter operates correctly around the MPP, even $P_{MPP}$ can be determined. Otherwise a separate measurement has to be made to obtain $P_{MPP}$.

Fig. 12: Cloud diagram of an inverter Solarmax DC30+ at 25kW

Fig. 11: I-V-curve of the highly stable 25kW PV-generator-simulator developed by HTA Burgdorf.

As these new PV generator simulators were available only in 2000, exact MPPT-efficiency measurements could be made only since then.

Fig. 9: RF voltages produced by a Convert 2000 on the AC side and limits of EN55014/EN50081-1.

Fig. 10: RF voltages produced by a Convert 2000 on the DC side and limits of EN55014.
at the same connection point, which caused three hardware failures. Moreover, in 2001 an overvoltage probably caused by a storm occurred at a location with several inverters in parallel. Since then, a slight increase in the number of hardware defects per inverter operation year can be observed, which is partly due to the increasing average age of the inverters. Partly they are caused by manufacturers that do not understand or even deny the some requirements (e.g. sufficient RF suppression also on the DC side). With increasing DC-AC conversion efficiency, where further improvements become more and more difficult, also a reasonably high (and stable!) MPPT-efficiency becomes more important. This property, however, is quite difficult to test, because sophisticated equipment is necessary. Long-term reliability (not only of the inverter, but also of the whole PV system) is also a major concern. A MTBF of a few years seems to be reached now with new inverters from experienced manufacturers. With the very good test facilities and nearly ten years of monitoring experience, HTA Burgdorf’s PV laboratory is prepared to carry out more and more sophisticated tests of inverters and to contribute to the further evolution of inverter technology. On demand manufacturers can have their products tested (prototypes or products already on the market) to assess and improve their performance.

**3. RELIABILITY AND INVERTER DEFECTS**

Monitoring of inverter reliability mentioned already in earlier papers [2, 3] could be continued in the last few years, too. As most inverters monitored became operational in 1994 – 1996, reliability was best in the years 1997 to 1999. Since then, a slight increase in the number of hardware defects per inverter operation year can be observed, which is partly due to the increasing average age of the inverters. Moreover, in 2001 an overvoltage probably caused by a thunderstorm occurred at a location with several inverters at the same connection point, which caused three hardware defects, that also increased the number of defects in 2001.

Quite often, new inverters from inexperienced manufacturers have sporadic MPPT-problems (see Fig. 14). Monitoring of inverter reliability mentioned already in earlier papers [2, 3] could be continued in the last few years, too. As most inverters monitored became operational in 1994 – 1996, reliability was best in the years 1997 to 1999. Since then, a slight increase in the number of hardware defects per inverter operation year can be observed, which is partly due to the increasing average age of the inverters. Moreover, in 2001 an overvoltage probably caused by a thunderstorm occurred at a location with several inverters at the same connection point, which caused three hardware defects, that also increased the number of defects in 2001.

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**4. CONCLUSIONS**

Performance and quality of inverters especially from experienced manufacturers have improved considerably in the last decade. However, there are still remaining problems. Partly they are caused by manufacturers that do not understand or even deny the some requirements (e.g. sufficient RF suppression also on the DC side). With increasing DC-AC conversion efficiency, where further improvements become more and more difficult, also a reasonably high (and stable!) MPPT-efficiency becomes more important. This property, however, is quite difficult to test, because sophisticated equipment is necessary. Long-term reliability (not only of the inverter, but also of the whole PV system) is also a major concern. A MTBF of a few years seems to be reached now with new inverters from experienced manufacturers. With the very good test facilities and nearly ten years of monitoring experience, HTA Burgdorf’s PV laboratory is prepared to carry out more and more sophisticated tests of inverters and to contribute to the further evolution of inverter technology. On demand manufacturers can have their products tested (prototypes or products already on the market) to assess and improve their performance.

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**REFERENCES**


Further information about the research activities of HTA Burgdorf’s PV laboratory on the internet: [http://www.pvtest.ch](http://www.pvtest.ch)