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).

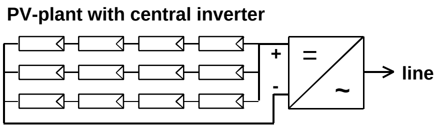

Fig. 1: PV plant with central inverter

Three phase inverters often were grid-commuted and used thyristors. Smaller single phase inverters were often designed according to the concept of SI-3000 (self-commuted 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).

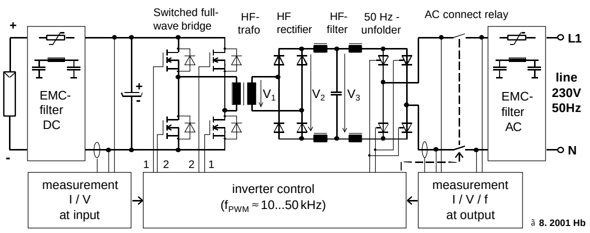

Fig. 2: PV inverter with HF transformer (e.g. SI-3000)

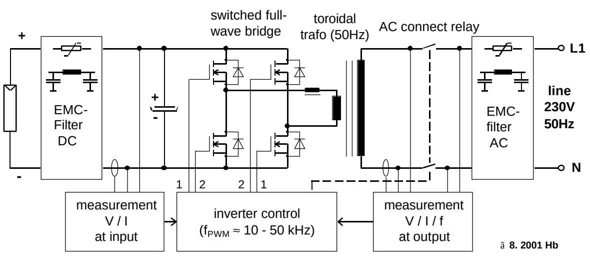

Fig. 3: PV inverter with LF transformer (e.g. TCG 3000)

Soon also self commuted 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 lage sized) module, thus eliminating completely the DC wiring (see fig. 4).

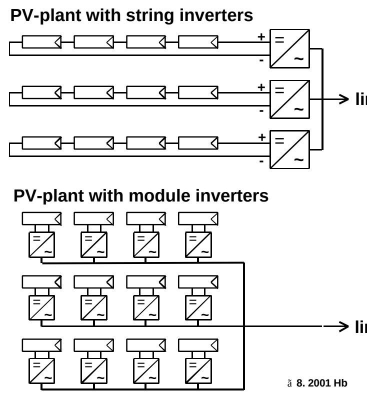

Fig. 4: PV plants with string- and module inverters

A key issue in all inverter designs was always DC-AC conversion efficiency η . 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).

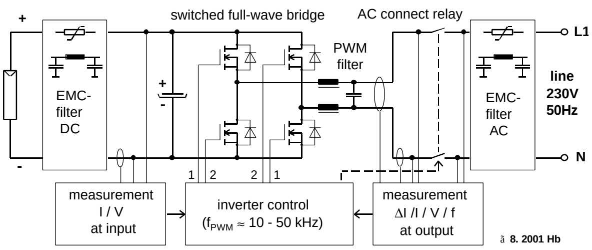

Fig. 5: PV inverter without transformer

2. MAIN TEST RESULTS

Type	Year of test	S_N [kVA]	V_{DC} (typ.) [V]	European efficiency η_{EU} [%]	Transformer	Harmonics of current (0.1-2kHz)	EMC AC	EMC DC	Sensitivity to tele-control signals	Islanding
SI-3000	89	3.0	48	90	HF	0	-	-	0 3)	-/++ 3)
SOLCON	90/91	3.3	96	90	HF	+	- 1)	- -	+ 3)	-/++ 3)
EGIR 10	91	1.7	165	89	LF	-	-	-	n.t.	n.t.
PV-WR-1500	91	1.5	96	85.5	HF	++	0	-	0	++ 5)
ECOVERTER	91/92	1.0	64	92	HF	++	0	0	+	++
PV-WR-1800	92	1.8	96	86.5	HF	+	+ +	0	0	++ 5)
TCG 1500	92	1.5	64	89.5	LF	+	+ 1)	0 1)	++	-/++ 3)
TCG 3000	92	3.0	64	91.5	LF	0	+ 1)	0 1)	++	-/++ 3)
EcoPower20 *	94/95	20	760	92.6	LF 6)	0	0/+ 1)	++	++	0
Solcon3400	94/95	3.4	96	91.9	HF	0	0/+ 1)	0	+	++
NEG 1600	95	1.5	96	90.4	LF	+	++	0	++	++
SolarMax S	95/98	3.3	550	91.7	no 6)	+	-/+ 7) 8)	+	++	0/++3)
SolarMax20 *	95	20	560	89.4	LF	0	+	-/0 1)	++	++
TCG II 2500/4	95	2.2	64	91.9	LF	0	+	0	++	++
TCG II 2500/6	95	2.2	96	90.4	LF	0	+	-	++	++
TCG II 4000/6	95	3.3	96	90.2	LF	0	0/+ 2) 8)	-/++ 2)	++	++
Edisun 200	95/96	0.18	64	90.7	HF 6)	++	++	0 4)	++	++
SPN 1000	95/96	1.0	64	89.8	LF	+	+	++	0	++
Sunrise 2000	96	2.0	160	89.3	LF	0	++	+	0	++
SWR 700	96	0.7	160	90.8	LF	0	0 8)	++	+	++
TCG III 2500/6	96	2.25	96	91.5	LF	+	+ 8)	++	++	++
TCG III 4000	96	3.5	96	91.9	LF	+	+ 8)	++	++	++
TC Spark	98/99	1.35	180	90.6	LF	++	+ 8)	++	++	++
OK4E-100	98/99	0.1	32	90.3	HF	++	+	- - 4)	++	0
Solcolino	99/00	0.2	64	90.6	HF 6)	++	0	- - 4)	++	++
Convert 2000	01	1.8	300	94.2	no 6)	++	+	+	++	++
Convert 4000	99/00	3.8	550	92.5	no 6)	++	+ 8)	++	++	++
SWR1500	99/00	1.5	400	94.4	no 6)	++	+ 8)	++	++	++

++	very good, meets the standard easily	1)	after modification by HTA Burgdorf
+	good, meets the standard	2)	with optional DC-choke
0	satisfactory, meets the standard nearly	3)	with new control software
-	insufficient, does not meet the standard	4)	sufficient for module inverters (PV array small)
- -	bad, does not meet the standard at all	5)	with 3-phase connection only
n.t.	not tested	6)	without galvanic separation DC-AC
	HF = high frequency, LF = low frequency (50Hz)	7)	new, improved model
*	3 phase device	8)	slightly higher than limits for f < 300kHz

Table 1: Key specifications and main test results of the inverters tested by HTA Burgdorf from 1989 to 2001. European efficiency η_{EU} was calculated with the following formula (index value = percent of rated load):

$$\eta_{EU} = 0.03\eta_5 + 0.06\eta_{10} + 0.13\eta_{20} + 0.1\eta_{30} + 0.48\eta_{50} + 0.2\eta_{100}$$

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 η_{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).

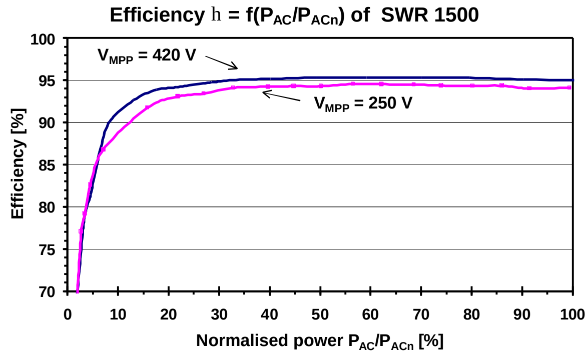

Fig. 6: Efficiency vs. normalised power (referred to rated power) for SWR 1500 (no transformer).

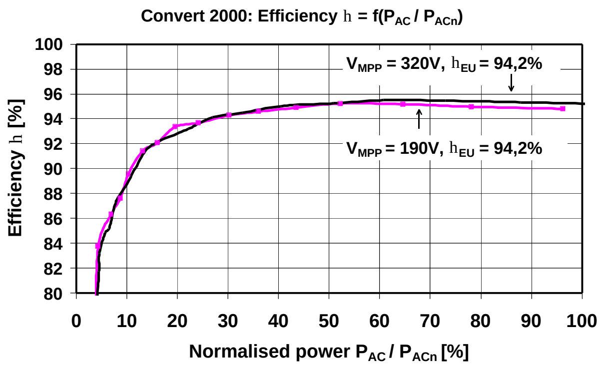

Fig. 7: Efficiency vs. normalised power (referred to rated power) for Convert 2000 (no transformer).

2.2 Harmonics of Current

Except EGIR10 all inverters tested were self-commuted 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 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.

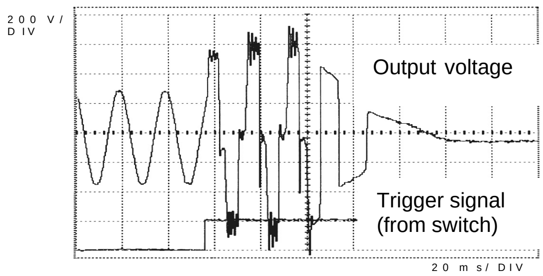

Fig. 8: Voltage at AC output of a SWR700, when the connection to line is interrupted under load (no load to inverter). Peak voltage observed is 760V.

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) superimposed 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 55dBµV 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.

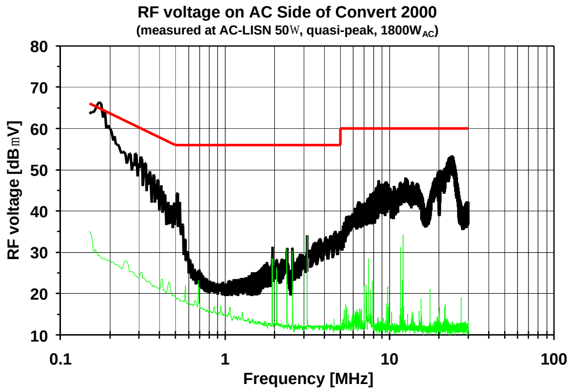

Fig. 9: RF voltages produced by a Convert 2000 on the AC side and limits of EN55014/EN50081-1.

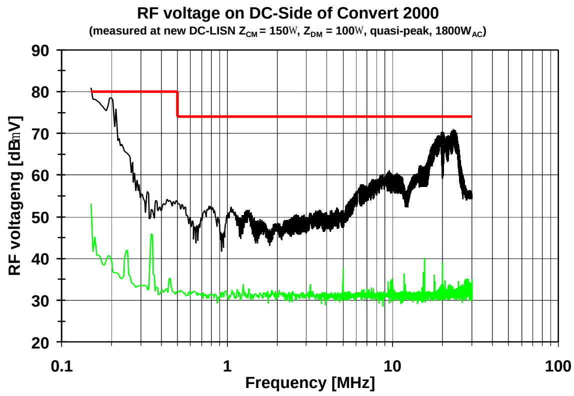

Fig. 10: RF voltages produced by a Convert 2000 on the DC side and limits of EN55014.

2.7 Maximum Power Point Tracking (MPPT)

Sporadic MPPT-problems often occur in the first designs from new manufacturers. Apart form 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 $P_{MPP} \leq 25$ kW, $I_{SC} \leq 40$ A and $V_{OC} \leq 750$ 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.

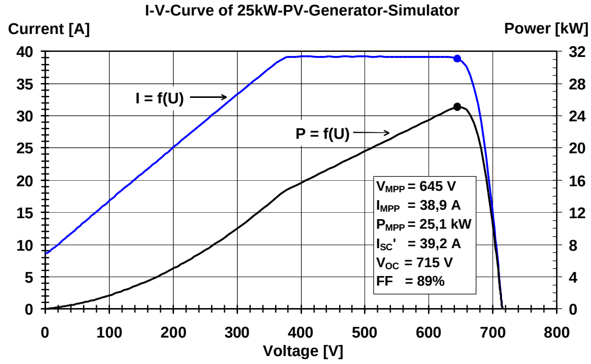

Fig. 11: I-V-curve of the highly stable 25kW PV-generator-simulator developed by HTA Burgdorf.

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

2.7.2 Measurement of MPP Tracking Efficiency

Static MPP tracking efficiency can be defined as:

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

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}.

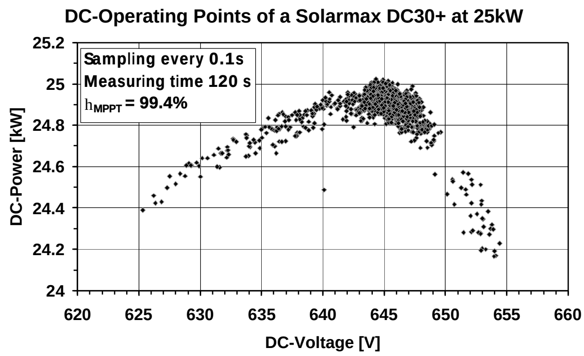

Fig. 12: Cloud diagram of an inverter Solarmax DC30+ operating at the I-V-curve of the PV simulator according to fig. 11. Measured h_{MPPT} was 99.4%, thus MPP-tracking is very good.

Until now, only a few inverters could be tested thoroughly for MPPT. When the inverters were measured close to the middle of their MPPT-voltage window in the range from 10% of rated power and up, measured η_{MPPT} was more than 97 % with most inverters tested (example: see fig. 13). For power levels > 30% of rated power, η_{MPPT} was even 99% or higher. However, near (but still within) the limits of the MPPT-voltage η_{MPPT} decreased considerably with some inverters. As this is quite difficult to test, the manufacturers may not be aware of that.

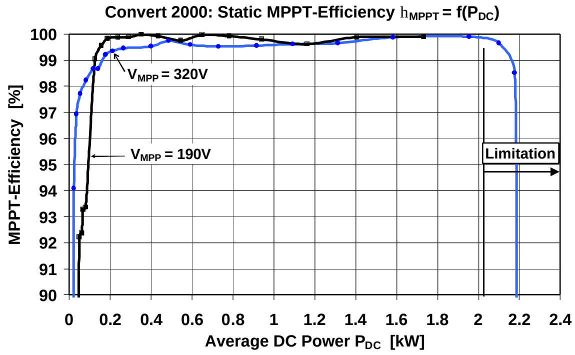

Fig. 13: Static MPP-tracking efficiency h_{MPPT} vs. MPP-power of PV generator simulator of a the new inverter Convert 2000.

Quite often, new inverters from inexperienced manufacturers have sporadic MPPT-problems (see fig. 14).

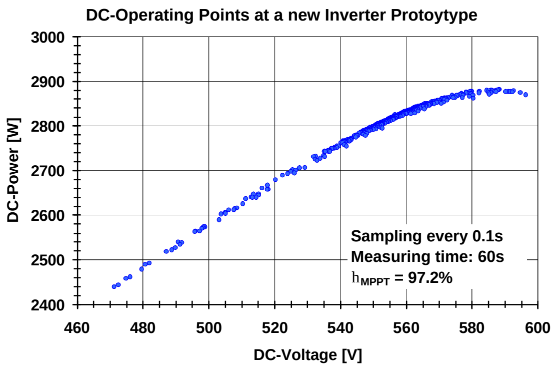

Fig. 14: Cloud diagram of a prototype of an new inverter. This device has a sporadic MPPT-problem.

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.

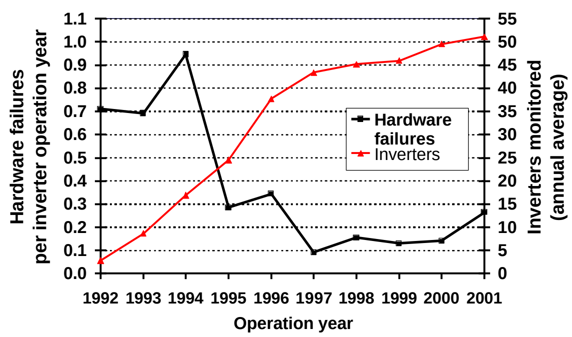

Fig. 15: Inverter defects and average number of inverters monitored by HTA Burgdorf (first 8 months of 2001 converted into a full year).

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.

IMPORTANT NOTICE

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Further information about the research activities of HTA Burgdorf's PV laboratory on the internet: **http://www.pvtest.ch**