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PV-INVERTERS FROM 1KW TO 3KW FOR GRID-CONNECTION: RESULTS OF EXTENDED TESTS

H. Häberlin and H.R. Röthlisberger
Ingenieurschule / Polytechnic, CH-3400 Burgdorf, Switzerland
Phone 034 / 21 41 41 , Fax 034 / 23 15 13

ABSTRACT

Inverters may affect other electrical equipment by overvoltage, harmonics or radio frequency interference (RFI). On the other hand normal operation of PV-inverters can be affected by events on the mains (e.g. overvoltages, telecontrol signals). In Switzerland such problems have occurred in many grid-connected PV-installations in the last few years (sudden inverter failures with hardware defects or adverse effects on adjacent electronic equipment).

Since 1988 our PV-laboratory has operated a grid-connected PV-installation of 3kW. Inverters from different manufacturers for single-phase-operation with rated power between 1kW and 3kW have been thoroughly tested under continuous computer monitoring, allowing detailed analysis of inverter failures during the tests. Test duration was between a few weeks and more than one year. Special care was taken to avoid adverse RFI-influence on measurements. Important results were verified by additional measurements with high precision instruments completely independent of computer data acquisition. Manufacturers or general representatives in Switzerland were informed as soon as possible about test results and weak points of their inverter.

1. MEASURING CONCEPT

Our PV test installation consists of 54 modules ARCO M55 (2.97kWp). Every second all relevant data are sampled by a personal computer (see Fig. 1). Under normal operating conditions the PC stores average values (over a 1 minute period). In case of a failure, error files are being generated, containing all data picked up in the time interval when the error occurred, allowing detailed analysis of the causes of the event.

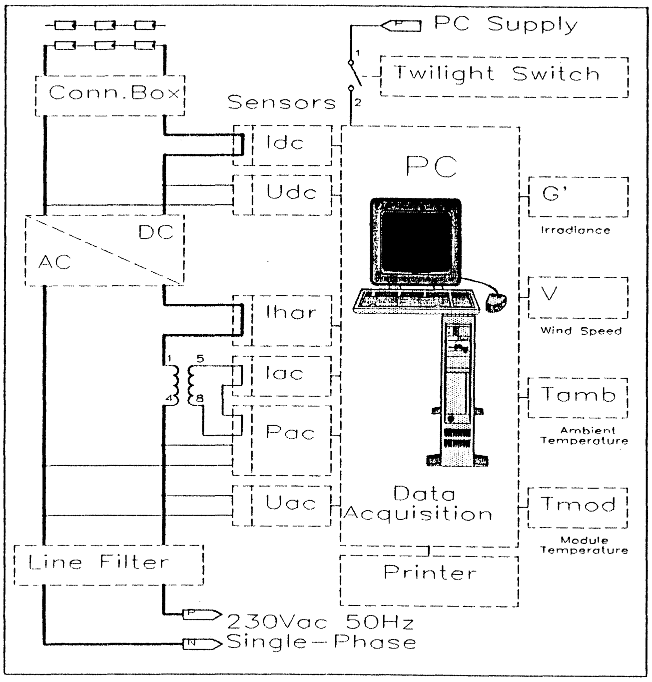

Fig. 1: Measuring concept of PV test site SOLAB 3.

2. MAIN TEST RESULTS

During our tests, 8 different inverters were used (only one inverter of each type). They were bought on the market (SI-3000, SOLCON) or provided especially for these tests by the distributor or manufacturer.

Two 3kW-inverters, SI-3000 from Photoelectric Inc., USA, and SOLCON, from Hardmeier, Switzerland, have been tested continuously for more than 15 months. Three other inverters, PV-WR1500 (1.5kW) and PV-WR1800 (1.8kW) from SMA, Germany and TOP CLASS 3000 (3kW) from ASP, Switzerland, were tested for about 2 months. Shorter tests up to two weeks were carried out with EGIR10 (1.5kW), TOP CLASS 1500 (1.5kW) from ASP, Switzerland and ECOVERTER 1000 (1kW) from Victron, the Netherlands.

Table 1 shows the most important specifications of the inverters and the main results of our inverter tests.

2.1 Efficiency

The "European efficiency" indicated in table 1 was calculated with the formula below (index value = percent of rated load):

$$n = 0.03n_5 + 0.06n_{10} + 0.13n_{20} + 0.1n_{30} + 0.48n_{50} + 0.2n_{100} \quad (1)$$

Fig. 2 and 3 show efficiency vs. normalized DC-input-power of the inverters tested. Two figures were used to allow a clear identification of each inverter. Top efficiency is between 93% (ECOVERTER 1000 and TOP CLASS 3000) and 90% (PV-WR 1500 and 1800). Low power efficiency is very good for SOLCON, TOP CLASS 3000 and ECOVERTER 1000.

2.2 Harmonics

Harmonic currents injected into mains by SOLCON [1], PV-WR-1500 and 1800, TOP CLASS 1500 and ECOVERTER 1000 are below the limits of European standard EN-60555-2 and therefore should not cause any problems in practical operation. Values for SI-3000 [1] and TOP CLASS 3000 (see fig. 4) and especially for EGIR10 [3], are a little higher than the limits and could cause some problems at locations with high mains impedance [3].

Typ	S_N [VA]	U_{DC} [V]	Turn-on power [W_{DC}]	Trans-former	European efficiency [%]	Principle s: self-com-mutated l: line-com-mutated	Har-monics of current (<2kHz)	EMI AC	EMI DC	Sensitivity to telecontrol signal	Audi-ble noise
SI-3000	3000	48	100	HF	90	s	o	-	-	o (mod)	-
SOLCON	3300	96	60	HF	90	s	+	- (mod)	- -	+ (mod)	+ +
PV-WR-1500	1500	96	20	HF	85,5	s	+ +	o	-	o	+
PV-WR-1800	1800	96	20	HF	86,5	s	+	+ +	o	o	o
TOP-CLASS 1500	1500	64	15	LF	89,5	s	+	+(mod)	o (mod)	+ +	+
TOP-CLASS 3000	3000	64	18	LF	91,5	s	o	+(mod)	o (mod)	+ +	+
ECOVERTER 1000	1000	64	10	HF	92	s	+ +	o	o	+	+
EGIR 10	1700	165	17	LF	89	l	-	-	-		-

+ +	very good, meets the standard easily	-	insufficient, doesn't meet the standard
+	good, meets the standard	- -	bad, doesn't meet the standard at all
O	satisfactory, meets the standard nearly	(mod)	after modification

Table 1: Main results of our inverter tests.

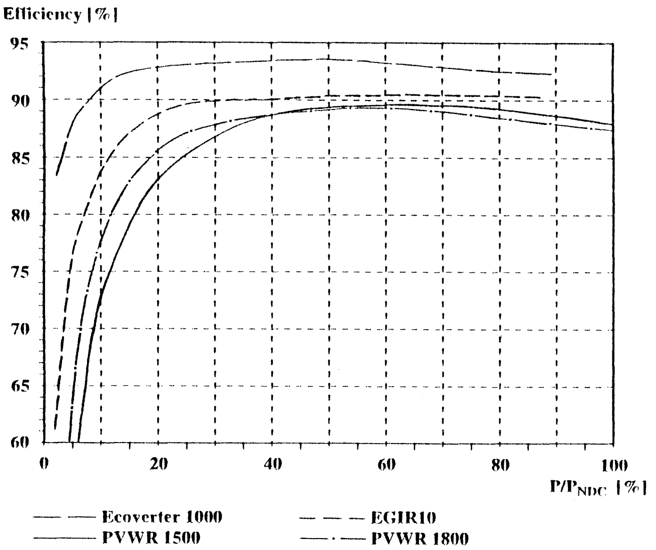

Fig. 2: Efficiency vs. normalized (referenced to rated power) DC-input-power (ECOVERTER 1000: 1kW, PV-WR-1500 and EGIR10: 1.5kW, PV-WR1800: 1.8kW).

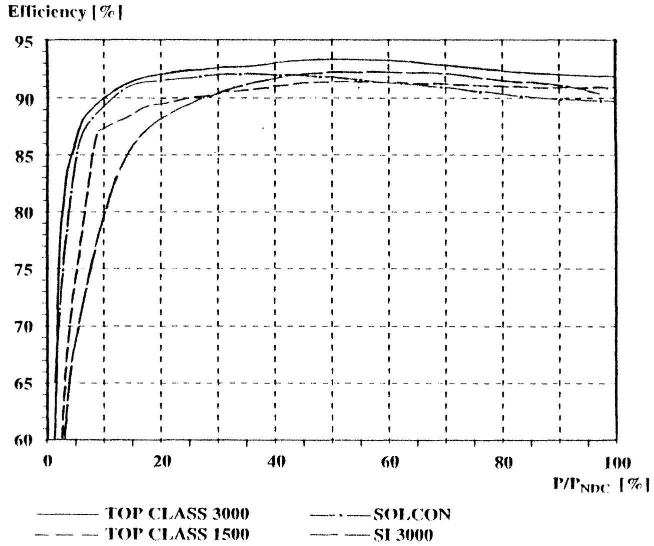

Fig. 3: Efficiency vs. normalized (referenced to rated power) DC-input-power (TOP CLASS 1500: 1.5kW, SI-3000, SOLCON and TOP CLASS 3000: 3kW).

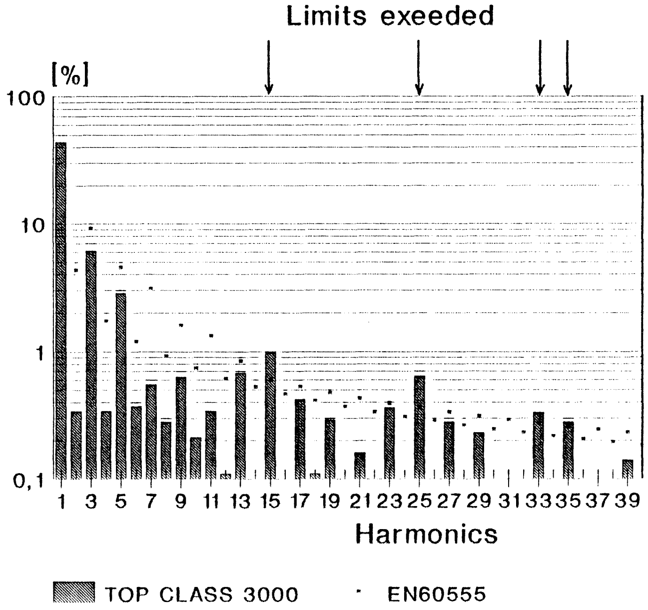

Fig. 4: Current harmonics of TOP CLASS 3000 at Pac = 2,7kW (percent values referenced to 25A).

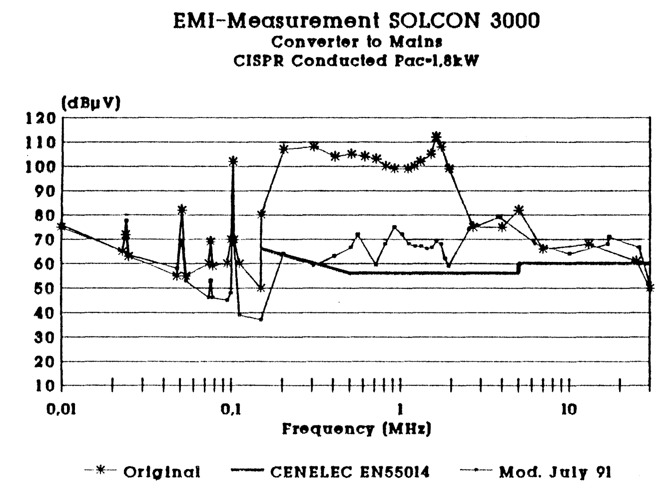

Fig. 5: RF-voltage vs. frequency for SOLCON 3300 on AC before and after modification of July 1991 .

2.3 Radio Frequency Interference

A few years ago inverter manufacturers did not care about radio frequency (RF) voltages generated by their inverters (see fig. 5, upper curve). Problems in the field and perhaps also some of our papers [2] made them change their minds. RF-voltages produced by new designs (e.g. PV-WR-1800, ECOVERTER 1000 and modified versions of TOP CLASS, see fig. 6) are now clearly below the limits of EN55014 on AC and at least close to them on DC.

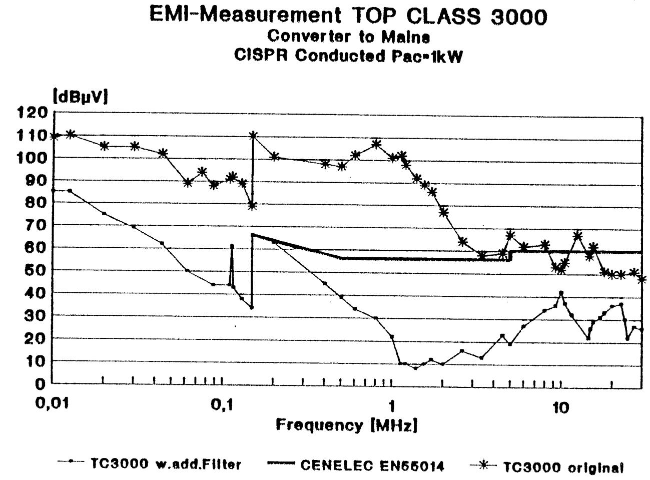

Fig. 6: RF-voltage vs. frequency for TOP CLASS 3000 on AC without line filter and with additional line filter (recommended).

2.4 Islanding

After loss of line power, inverters for grid-connection should shut down quickly to avoid dangerous situations. SI-3000, SOLCON and TOP CLASS 1500 had initial problems with islanding under special load conditions (matched load) after loss of line voltage [2]. These problems could be cured by a software change. PV-WR-1500 and 1800 must be connected to all three phases according to the manufacturer's recommendation (although only a single phase device) to avoid islanding problems [3].

2.5 Reliability and Inverter Defects

In 15 months of operation of SI-3000 4 hardware defects occurred. Three of them were caused by a telecontrol signal (f=317Hz) on the mains [2]. In 17 months of operation of SOLCON there were also four hardware defects. Three of them were caused by low-frequency overvoltage.

Fig. 7 shows such a defect on April 6, 1991, caused by a 50Hz-overvoltage of 242V at the connection point. At the very moment when the defect occurred, irradiance was very high and power demand was low.

Fig. 8 shows a defect on May 18, 1991 under similar conditions with a line voltage of 240V. The telecontrol signal with a frequency of 317 Hz occurring at 1200 increased total voltage to an amount that caused an inverter failure.

In July 1991 a design change increased safe voltage level to 247V. Since then no further hardware defects were registered.

As sensitivity to telecontrol signals depends on voltage and frequency of the signal as well as on line voltage, we developped a telecontrol signal simulator. We can now test PV-inverters at different voltages and frequencies and not only at the frequencies used by our local power company. Fig. 9 shows the sensitivity of the PV-WR1800 to telecontrol signal voltage vs. frequency. The inverter is stopped by higher voltages. After some time (< 2 minutes in all cases) the inverter restarts automatically.

PV-WR1500 has a similar sensitivity to telecontrol signals. In figure 10 you can see two short losses of AC power at 1200 and 1600 caused by such signals in practical operation.

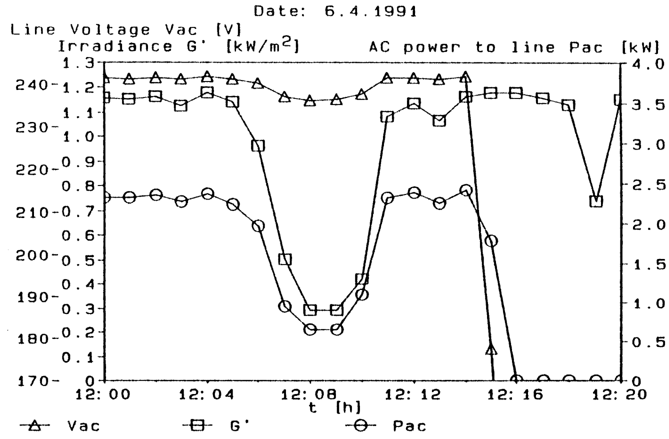

Fig. 7: SOLCON hardware defect caused by 50Hz-overvoltage (242V) on mains.

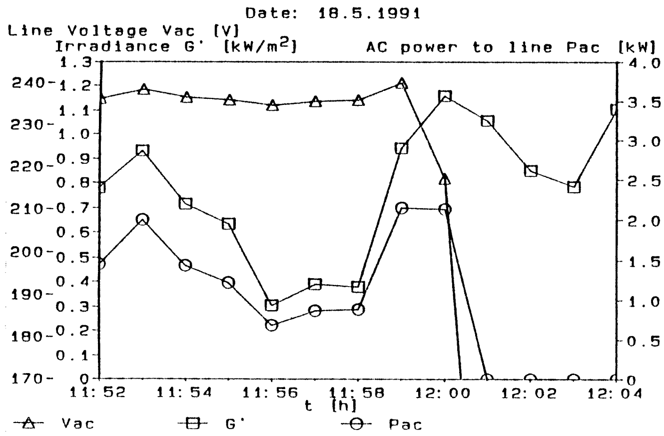

Fig. 8: SOLCON hardware defect caused by high 50Hz-voltage (about 240V) and superimposed telecontrol signal of 317Hz at 1200.

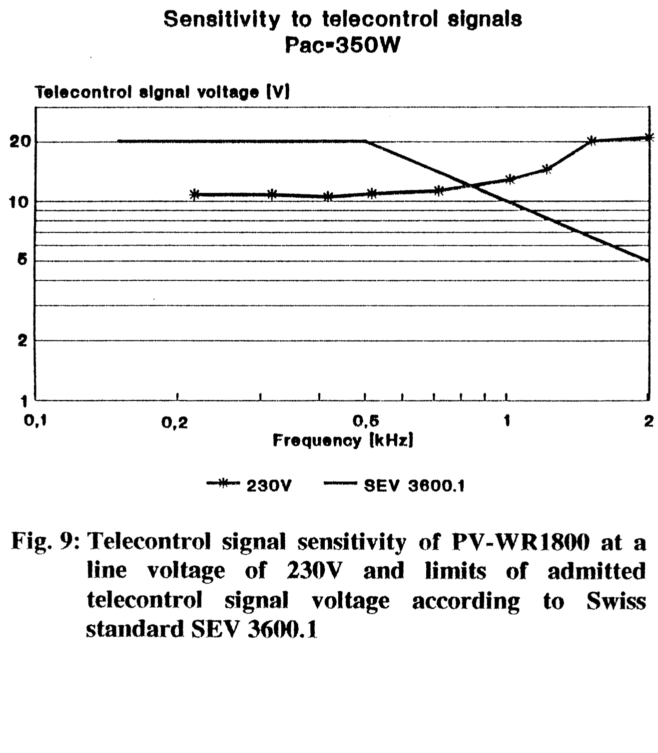

Fig. 9: Telecontrol signal sensitivity of PV-WR1800 at a line voltage of 230V and limits of admitted telecontrol signal voltage according to Swiss standard SEV 3600.1

During more than 2 month of operation of PV-WR1500, PV-WR1800 and TOP CLASS 3000 no hardware defect occurred at our test site. During the shorter tests of EGIR10, ECOVERTER 1000 and TOP CLASS 1500 there were also no hardware defects.
However, there were some problems with a prototype version of TOP CLASS 3000 at a location where we also pick up data for another project (yield and reliability of PV-inverters). Several sudden stops which needed manual restart and one hardware defect were observed. In this project the number of sensors and data is reduced compared to our test site, therefore the reason for this defect could not be determined. No further problems were encountered so far after replacement of the prototype inverter by the inverter previously tested at our test site.

2.6 Maximum Power Tracking Problems

Many new inverter designs have sporadic maximum power tracking problems. Such problems were observed with early versions of SOLCON, the prototype version of TOP CLASS 3000 that caused also other problems (see above) and also a new three-phase inverter where we had access to data via modem. Such problems can only be detected by continuous monitoring of irradiance and AC-power over some time. They may be caused by software errors or internal electromagnetic interference problems. All problems observed could be cured by software or design changes in the meantime.

2.7 Power Limiting at high DC-Power Levels

PV-WR1500 and 1800 have a very interesting feature. When DC-input power is too high (e.g. due to a solar generator with nominal power at STC greater than rated DC-input power or owing to a cloud enhancement situation) these inverters leave the maximum power point of the solar generator. AC power fed into mains is limited to nominal AC power (see figure 10). Therefore solar generator power at STC can be up to 50% greater than rated DC-input power. Thus the peak power problem in the utility grid that may be caused by a widespread use of PV-inverters in the future [1] is alleviated considerably.

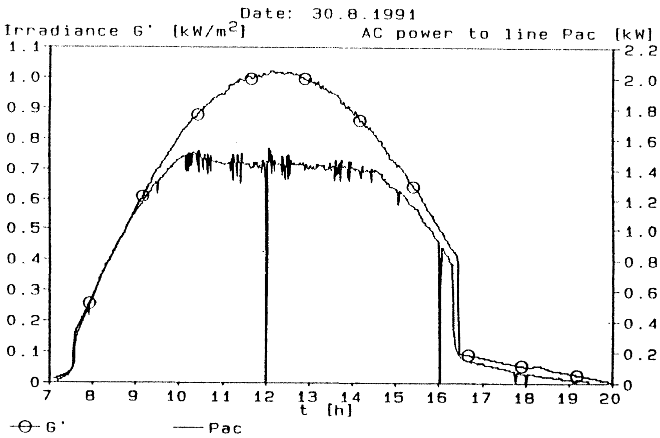

Fig. 10: When DC-input power is too high, AC power fed into mains by PV-WR1500 is limited to about 1.5kW (nominal DC-power of the solar generator used for this test at STC was about 2.5kW). Note also the short losses of AC power (without hardware defect) caused by a telecontrol signal at 1200 and 1600.

3. CONCLUSIONS

The purpose of our work was by no means to qualify the inverters tested and and to answer questions such as: "Which inverter is the best one?" Such a qualification is not intended and is not possible, as only one inverter of each type was tested for quite a short time compared to life expectancy. A serious answer would need several years of operation with several inverters of each type. After such a test most test results would be obsolete, as in the quickly developing PV-market most inverters would have been replaced by new designs in the meantime.
We wanted to learn as much as possible about normal and abnormal operation and the reasons of sudden defects of PV-inverters and to make a contribution to improvement and further development of their technology. We tried to be strictly neutral in doing so. Manufacturers or general representatives were informed about test results (of their inverter only) as quickly as possible. We also tried to transfer the knowledge acquired to PV specialists, PV system designers and power companies by means of several publications.
Our tests showed that reliabilty and performance of many PV-inverters currently on the market is not yet sufficient for many years of trouble-free operation. However, significant improvements were made in the last year by many manufacturers. More details about inverter problems and possible countermeasures can be found in [1] and [3].
In 1993 the peak power of our test site will be increased to 60kW allowing similar tests of larger inverters with three-phase-operation. In addition to the tests described in this paper, immunity of the inverters to voltage transients on AC and DC lines will also be tested.

IMPORTANT NOTICE

Information contained in this paper is believed to be accurate. Care has been taken to verify important results by independent measurements. However, errors can never be completely excluded. Therefore we disclaim any liability in a legal sense for correctness and completeness of the information or for any damage that might result from its use.

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