Results of Recent Performance and Reliability Tests of the Most Popular Inverters for Grid Connected PV Systems in Switzerland

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ABSTRACT: ISB's PV laboratory has carried out a lot of tests under continuous computer monitoring with small grid connected PV inverters in the past [1]. In spring 1994, a new test center for PV systems with a solar generator of 60 kWp (instead of the previously used 3 kWp) became operational [2]. In this paper the ***results of intensive tests*** of some recently developed inverters (1.5kW to 20kW) used in many grid connected PV systems in Switzerland are presented. Tests were performed in 1994 and 1995 under continuous computer monitoring at ISB's new PV test site. In addition, data obtained from an analytical monitoring project in the Canton of Berne [3] are used to get ***information about reliability*** of older and newer inverter models.

1. Test Program

The most important properties measured at ISB's test site were DC-AC conversion efficiency, harmonics, RF interference (RFI) on DC and AC side, islanding and sensitivity to telecontrol signals. MPP tracking quality of the inverters can also be monitored by a new method using normalized representation [4].

The following inverters were tested for at least one year:

- **ECOPOWER 20** (20 kW, 3-phase, no galvanic separation DC-AC), made by Invertomatic AG, Switzerland
- **SOLARMAX 20** (20 kW, 3-phase, galvanic separation DC-AC) made by Sputnik AG, Switzerland
- **SOLCON 3400** (3.4 kW, single phase), made by Hardmeier, Switzerland
- **TOP CLASS 4000** (3.3 kW, single phase), made by ASP AG, Switzerland

2. Main Test Results

Short tests of at least a few days were carried out with a **TOP CLASS 2500/4** (2.2kW), a **TOP CLASS 2500/6** (2.2 kW) and a **SOLARMAX S** (3.3 kW, no transformer). A test stand for module and string inverters is also operational. Currently tests of a prototype of a module inverter of 200W are going on.

Table 1 shows the most important specifications and the main test results of the inverters tested.

„European efficiency“ was calculated with the formula below (index value = percent of rated load).

$$h = 0.03\, h_{5} + 0.06 h_{10} + 0.13 h_{20} + 0.1 h_{30} + 0.48 h_{50} + 0.2 h_{100}$$

Type	S_N	V_{DC}	European efficiency	Turn-on power	1: 1-phase 3: 3-phase	Trans-former	Harmonic content of current (<2kHz)	EMI AC	EMI DC	Sensitivity to telecontrol signal	Islan-ding	Audible noise
	[kVA]	[V]	[%]	[W_{DC}]								
EcoPower20	**20**	**760**	**92.6**	**450**	**3**	**LF**	**0**	**0/+ 1)**	**++**	**++**	**0**	**0**
SolarMax20	**20**	**560**	**89.4**	**283**	**3**	**LF**	**0**	**+**	**-/0 1)**	**++**	**++**	**0**
SolarMax S	**3,3**	**550**	**91.7**	**66**	**1**	**none**	**+**	**-/+ 1)**	**+**	**++**	**0/++ 4)**	**+/- 3)**
Solcon3400	**3,4**	**96**	**91.9**	**25**	**1**	**HF**	**0**	**0/+ 1)**	**0**	**+**	**++**	**++**
TCG II 4000/6	**3,3**	**96**	**90.2**	**26**	**1**	**LF**	**0**	**+**	**-/++ 2)**	**++**	**++**	**+**
TCG II 2500/6	**2,2**	**96**	**90.4**	**14**	**1**	**LF**	**0**	**+**	**-**	**++**	**++**	**+**
TCG II 2500/4	**2,2**	**64**	**91.9**	**15**	**1**	**LF**	**0**	**+**	**0**	**++**	**++**	**+**

++	**very good, meets the standard easily**	**1)**	**after ISB modification**
+	**good, meets the standard**	**2)**	**with optional DC ring core choke**
0	**satisfactory, meets the standard nearly**	**3)**	**switching with 9kHz**
-	**insufficient, doesn’t meet the standard**	**4)**	**with new control software**
- -	**bad, doesn’t meet the standard at all**		

Table 1 : Most important specifications and main test results of ISB's newest inverter tests.

The measuring concept, the test site used and some results of earlier tests are described in [1, 2, 3]. Due to space limitations, only a few highlights of the many new test results can be given here

2.1 DC-AC Conversion Efficiency

Especially partial load efficiencies of the inverters tested have increased considerably compared to earlier designs (e.g. SI-3000, PV-WR-1500, PV-WR-1800). For inverters with galvanic separation between DC and AC, peak efficiency is between 91.5% and 93%, European efficiency between 89.4% and 91.9% . Ecopower 20 without galvanic separation has a peak efficiency of 95% and a European efficiency of 92.6%.

Important notice: Where RF voltages were too high, efficiency measurements displayed in fig. 1 to 4 were made *including additional filters* to make possible a fair comparison between all inverters.

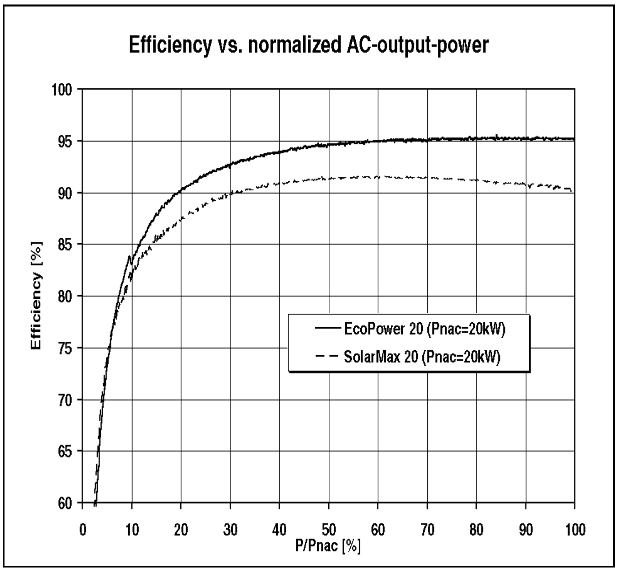

Fig. 1: Efficiency vs. normalized (referred to rated power) AC power of three-phase inverters **Ecopower 20** and **Solarmax 20**. Ecopower 20 without galvanic separation DC-AC, very high DC voltage from + to - (up to 1000V) and 3 connections on DC side (+, 0, -) has a peak efficiency that is about 3% higher. Solarmax 20 has full galvanic separation between DC and AC, only about 70% of the DC voltage and only 2 connections on the DC side.

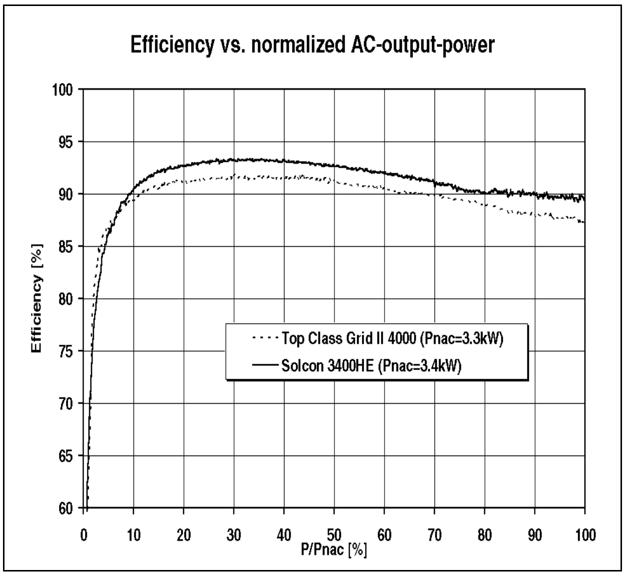

Fig. 2: Efficiency vs. normalized (referred to rated power) AC power of single-phase inverters **Solcon 3400** and **Top Class 4000**. Peak efficiency of Solcon is a little higher, whereas partial load efficiency is somewhat better with Top Class 4000.

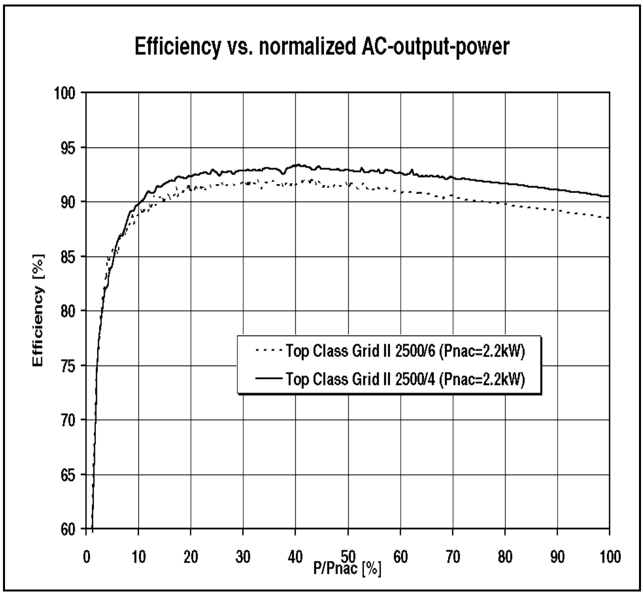

Fig. 3: Efficiency vs. normalized (referred to rated power) AC power of single-phase inverters **Top Class 2500/4** and **2500/6**. Efficiency of the low voltage model 2500/4 (for 4 modules in series) is a little higher than with 2500/6 (for 6 modules in series).

Efficiency of Solarmax S (without transformer) depends from temperature and switching frequency. At high heat sink temperatures, efficiency is nearly 1% lower than at low temperatures. When the inverter switches with 9kHz (when heat sink temperature is higher than about 66° C), audio emissions are quite annoying, but efficiency is about 1.5% higher than when it switches with 18kHz. The inverter normally operates with 18kHz (and therefore lower efficiency in the upper power range) and switches only to 9kHz, when heat sink temperature is high, in order to reduce heat dissipation. Fig. 4 shows efficiency of Solarmax S with low and high heat sink temperature and the average curve obtained during a few days of actual operation.

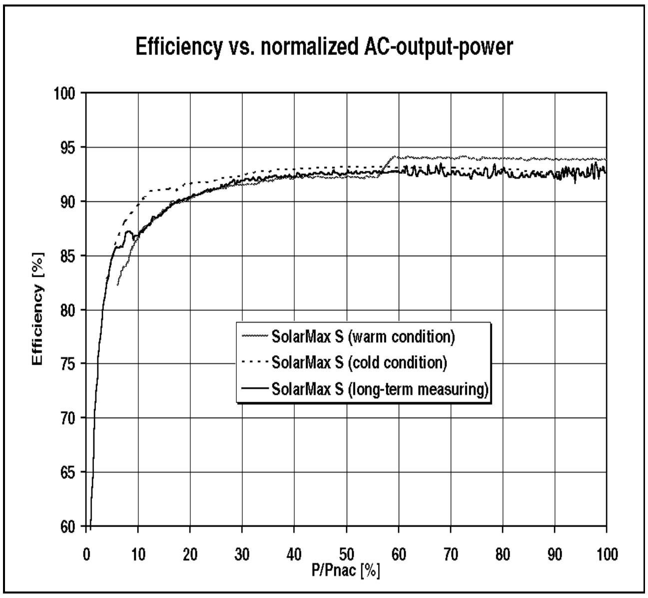

Fig. 4: Efficiency vs. normalized (referred to rated power) AC power of single-phase inverter **Solarmax S** (no transformer) with cold and warm heatsink and average curve registered during a few days of actual operation.

2.2 Harmonics

All inverters tested are self-commutated with high frequency pulse width modulation, therefore harmonic currents should not cause problems in practical operation, if the line impedance is not unusually high.

Harmonic currents injected into grid by the small inverters are mostly below the limits of EN60555-2. Only when the inverters are operated close to rated power, limits are exceeded slightly at some higher frequencies (usually >25th harmonic). The harmonics of current of the smaller inverters (Solcon 3400, Top Class 2500 and 4000) are completely below the limits of EN60555-2, when they are operated at power levels lower than 1.5 kWac to 2 kWac. Only when they are operated close to rated power, the limits may be slightly exceeded for some very few harmonics. For Top Class models this occurs usually at higher frequencies (>25th harmonic).

As Solcon 3400 tries to improve the sine wave form of the line voltage, at high power levels higher current harmonics may also occur at lower harmonic numbers (e.g. 3rd harmonic), if the corresponding harmonic voltage at the connection point (caused by other loads) is high enough. Harmonics of Solarmax S are below applicable limits at all power levels.

For equipment with line currents >16A a new standard for harmonic currents is being prepared. Harmonics of the two inverters of 20 kW are below the limits of draft IEC 1000-3-4 (stage 1, for unrestricted connection) for most frequencies. When operated at high power levels, the limits may be exceeded at a few frequencies (>25th harmonic).

However, if the apparent short-circuit power S_{cc} at the connection point is at least 120 times higher than the rated apparent power S_{equ} of the 3-phase inverter, higher limits are applicable (limits stage 2). This condition is usually met for a properly designed line connection of an inverter of this size. The harmonic currents indicated in Fig. 5 and 6 are below the limits of stage 2. Thus there should be no problems caused by harmonics in practical operation of a Solarmax 20 or an Ecopower 20.

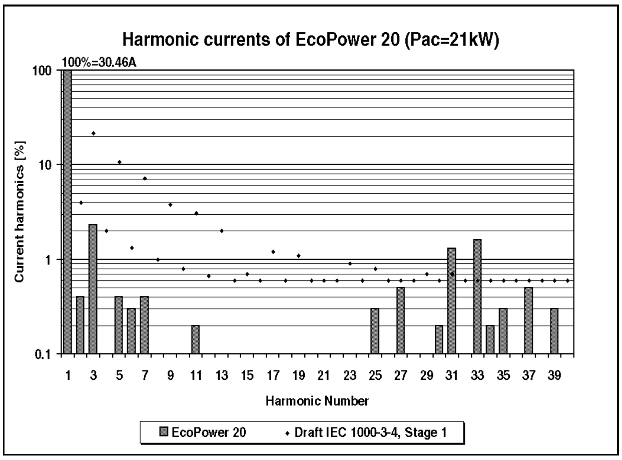

Fig. 5: Current Harmonics of Ecopower 20 at Pac=21,0kW compared to limits of draft IEC1000-3-4 (stage 1 for unrestricted connection) for line equipment >16A.

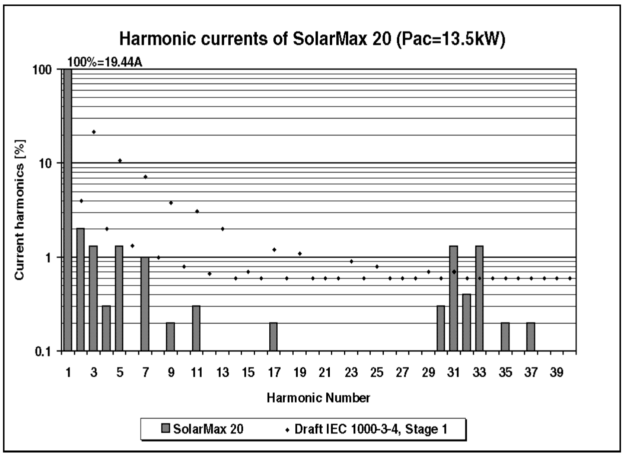

Fig. 6: Current Harmonics of Solarmax 20 at Pac=13,5kW compared to limits of draft IEC1000-3-4 (stage 1 for unrestricted connection) for line equipment >16A.

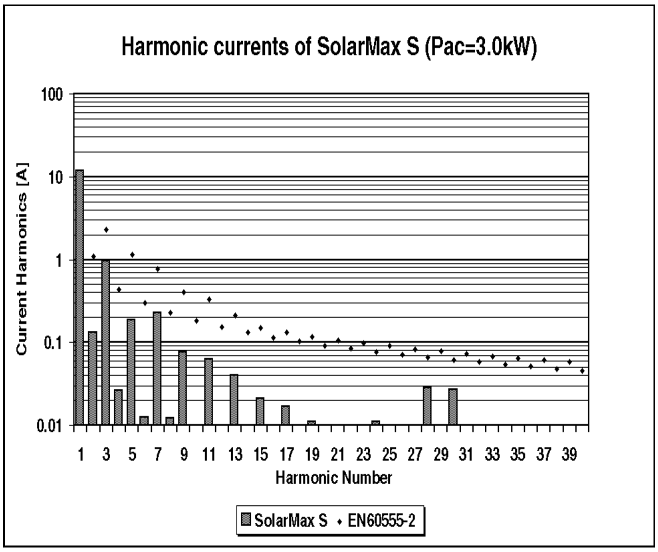

Fig. 7: Current Harmonics of Solarmax S at Pac=3,0kW compared to limits of EN60555-2.

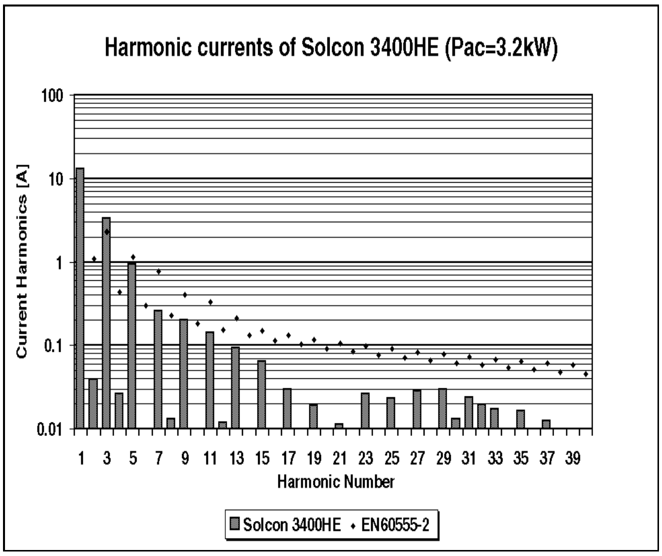

Fig. 8: Current Harmonics of Solcon 3400 HE at Pac=3,2kW compared to limits of EN60555-2.

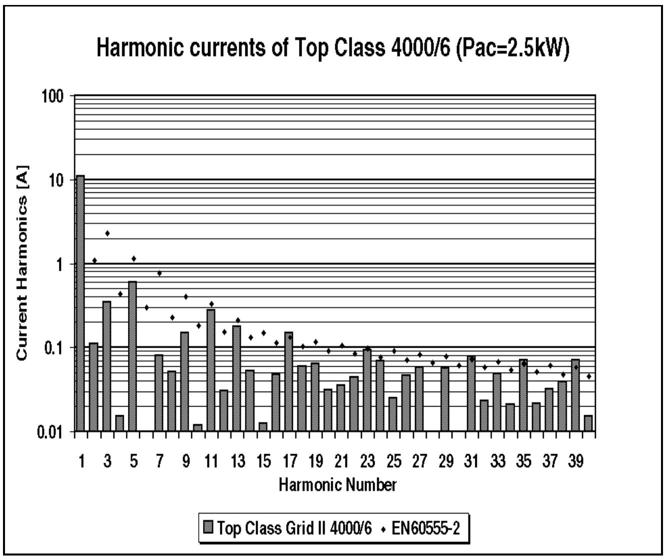

Fig. 9: Current Harmonics of Top Class Grid II 4000 at Pac=2,5kW compared to limits of EN60555-2.

2.3 Radio Frequency Interference (RFI)

Compared to earlier designs, RF voltages on AC side have been reduced considerably and are now mostly below applicable standards (e.g. EN55014 or EN50081). With some inverters, RF voltages on DC side are still too high. Low RF emissions on the DC side are not only desirable to reduce interference into adjacent electronic or radio equipment, but also to make possible the use of advanced protection devices (electrical arc detector) to prevent fire hazards on the DC side.

On AC side, RF voltage levels of most inverters tested at power levels between 50% and 100% of rated power were below the limits of EN55014. Top Class 2500 and 4000 were below these limits on all frequencies, Solarmax 20 and Solcon 3400 only for frequencies above 500 kHz. Solarmax S was considerably higher in its original version.

On DC side, only Ecopower 20 and Solarmax S were below the limits on all frequencies. All other inverters exceeded these limits at some frequencies slightly (Solcon 3400, Top Class 2500 and 4000) or considerably (Solarmax 20).

Where the limits of applicable standards were exceeded, additional filtering was provided in cooperation with the manufacturers. The results obtained with this additional filtering are also indicated in table 1 and in fig. 10 to fig. 19. Inverters with sufficient RFI filtering should be available now at least on request. *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 manufacturers do not realize yet.

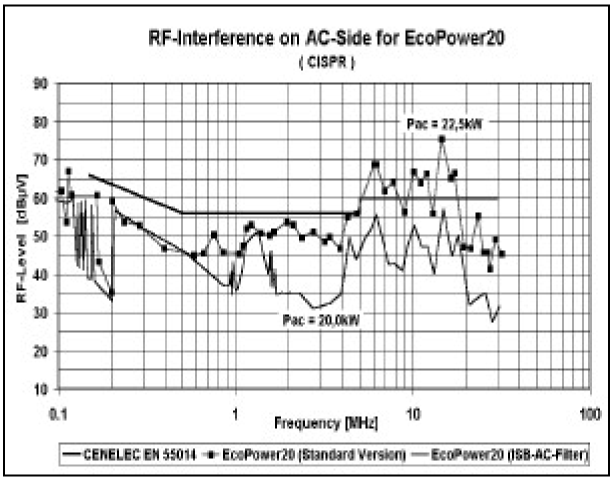

Fig. 10: RF voltages of Ecopower 20 on AC side at Pac≈20kW

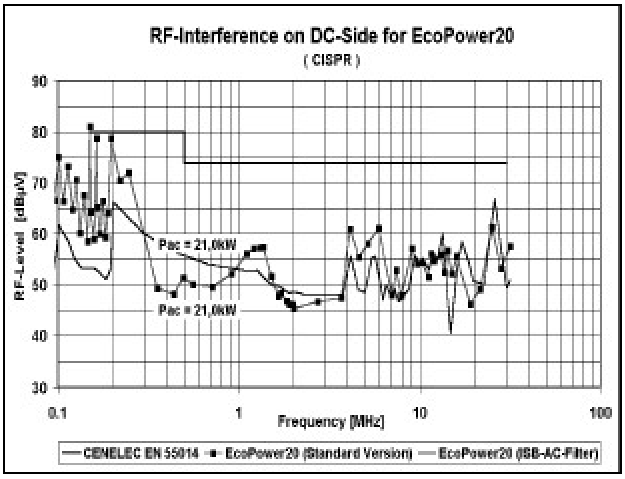

Fig. 11: RF voltages of Ecopower 20 on DC side at Pac=21,0kW

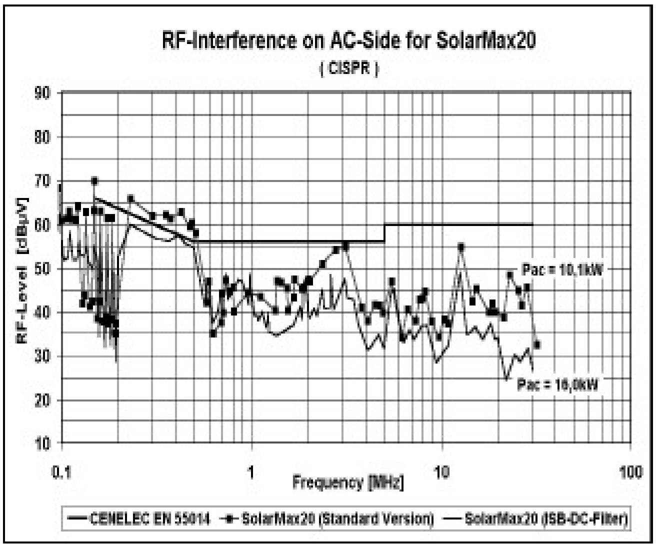

Fig. 12: RF voltages of Solarmax 20 on AC side

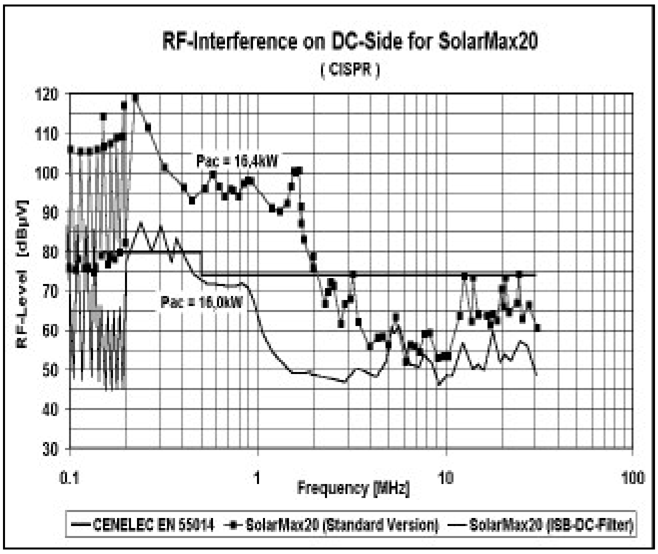

Fig. 13: RF voltages of Solarmax 20 on DC side

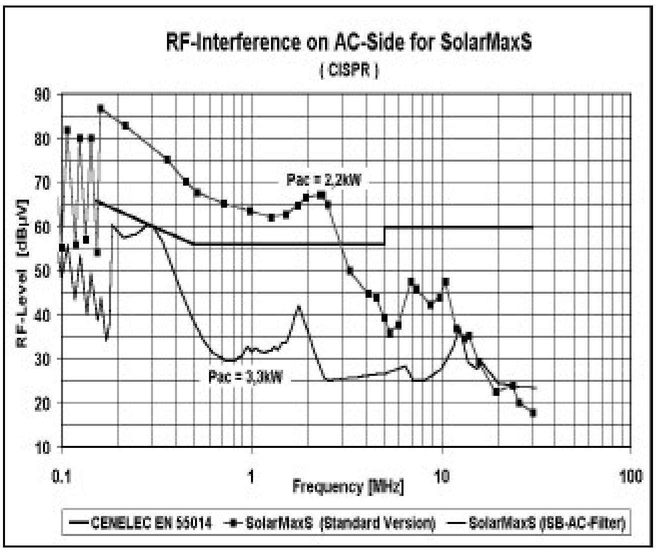

Fig. 14: RF voltages of Solarmax S on AC side

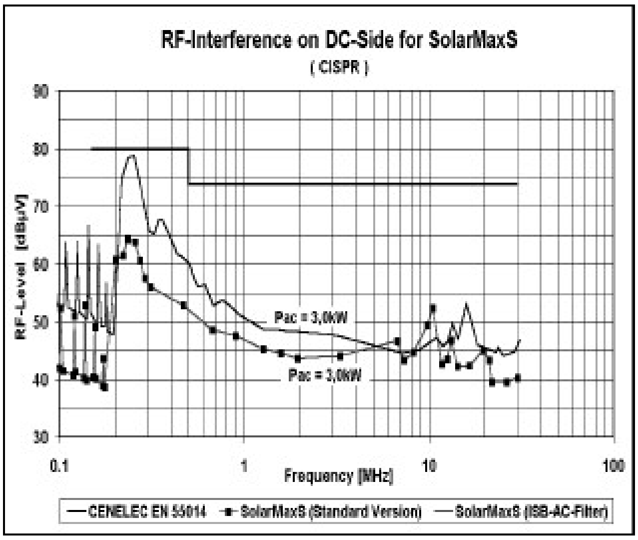

Fig. 15: RF voltages of Solarmax S on DC side at Pac=3,0kW

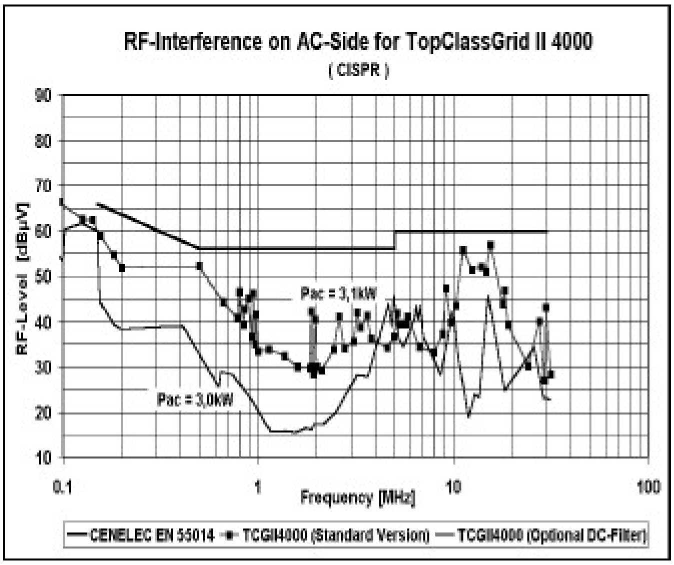

Fig. 18: RF voltages of Top Class 4000 on AC side at Pac≈3kW

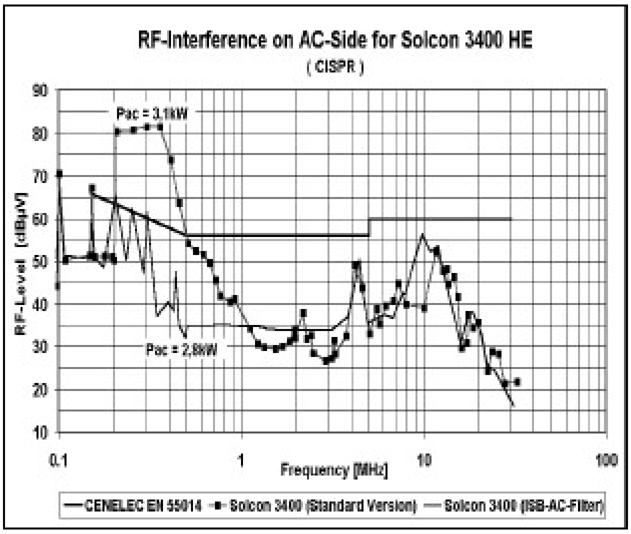

Fig. 16: RF voltages of Solcon 3400 HE on AC side

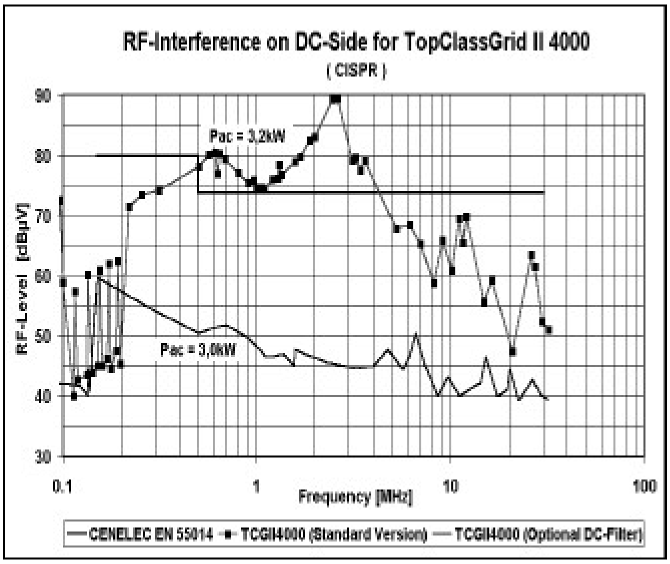

Fig. 19: RF voltages of Top Class 4000 on DC side at Pac≈3kW

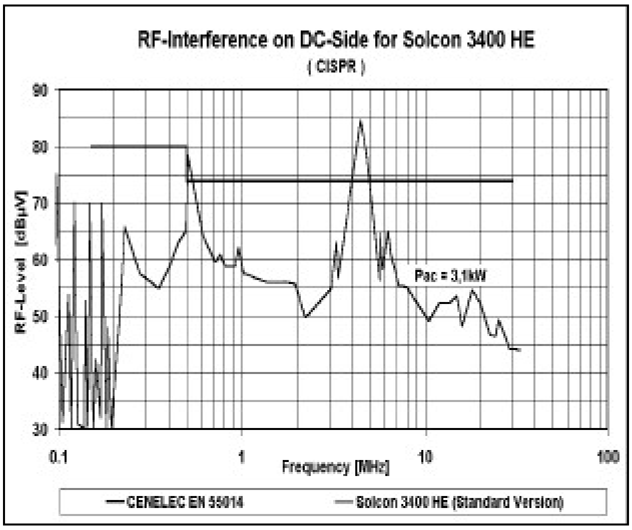

Fig. 17: RF voltages of Solcon 3400 HE on DC side at Pac=3,1kW

Quite often additional filtering on the DC side also reduces RF voltages on the AC side. This can be easily seen in fig. 10 to 19.

2.4 Islanding

All inverters tested are self-commutated, therefore they have a certain design inherent tendency for islanding. For safety reasons islanding is a major concern of many utilities. Among the smaller inverters up to 3.4 kW only Solarmax S had an initial problem with islanding under special load conditions (matched load) after loss of line voltage. This problem could be cured in cooperation with the manufacturer with a new version of the control software. Older models should be updated with this new software.

Similar tests were performed also with the two inverters of 20kW. Solarmax 20 had no islanding under all load conditions. Ecopower 20 had sometimes problems with islanding at higher load levels (Pac>14kW).

2.5 Sensitivity to Telecontrol Signals

All inverters were subjected to simulated telecontrol signals produced by ISB's telecontrol signal generator. Although quite high voltages (up to 18V) were used, no hardware defects occurred. Most inverters did not show malfunctions, too. Only Solcon 3400 sometimes switched off for a few seconds after a strong telecontrol signal, but resumed normal operation after a few seconds. Thus telecontrol signals should not cause any problems with these new inverters.

3. Reliability and Inverter Defects

In the past (1989-1991) a few hardware defects per year were usual. Reliability of new inverter designs monitored in this project is now by factors better (less than one hardware defect per year (exception: Ecopower 20)). At two plants, unusually heavy line transients were often observed that caused a few hardware defects, before the inverters were hardened against them. Under normal line conditions, the number of hardware defects would have been considerably lower. Telecontrol signals no longer cause hardware defects. Test results also show that energy production is not only affected by hardware defects, but also by sporadic inverter malfunctions that can be detected only by close monitoring used in this project.

Monitoring data used in this project were sampled at least every two seconds. From these data average values of 1 minute to 15 minutes were generated. Therefore it was possible to distinguish between hardware defects and other sporadic inverter malfunctions. Many more inverter problems than usual could be recognized. When only monthly values are used like in some other studies about inverter reliability, only really severe problems of long duration can be detected. However, due to cost limitations, the number of plants monitored in this project could not be very high. Thus a lot of major and minor inverter problems could be seen, but the size of the sample is relatively small for statistical purposes.

Location	Inverter	Months of opera-tion	Hardware failures per year				HW fail-ures	HW failures per inverter opera-tion year
			92	93	94	95	total	
Lohe/Burgdorf	PVWR 1500	37	0	0	0	0	0	**0.0**
IBI/Interlaken	PVWR 1800 (4x)	36	0	3	5	3	11	**0.9**
Lugeon/Burgdorf	Solcon 3300	39	0	0	0	0	0	**0.0**
Birg/Schilthorn	Solcon 3400HE	32	1	1	3	0	5	**1.9**
Schlossmatt 4	Solcon 3400HE	16			1	0	1	**0.8**
Jungfraujoch	TopClass 1800	22		0	0	0	0	**0.0**
Schlossmatt 3	TopClass 2500/6	16			0	0	0	**0.0**
Gfeller/Burgdorf	TopClass 3000	38	1	2	0	0	3	**0.9**
Aebi/Burgdorf	TopClass 3000	26		0	1	0	1	**0.5**
Schlossmatt 1	TopClass 4000/6	16			0	0	0	**0.0**
Schlossmatt 2	TopClass 4000/6	16			0	0	0	**0.0**
ISB/Burgdorf	TopClass 4000/6	15			0	1	1	**0.8**
ISB/Burgdorf	Solcon 3400HE	19			0	0	0	**0.0**
ISB/Burgdorf	SolarMax20	20			1	0	1	**0.6**
ISB/Burgdorf	EcoPower20	19			5	0	5	**3.2**

Table 2: Hardware defects registered at different locations

Table 2 shows the hardware defects registered at different locations and in different years. At Birg/Schilthorn, heavy line transients caused by the Schilthorn cableway led to a lot of hardware defects [3]. The inverter could be hardened against these unavoidable transients only in the end of 1994. The plant Aebi/Burgdorf is very close to a railway line, which induced also heavy line transients on the AC side. After suitable additional filtering no further hardware defects occurred. At Gfeller/ Burgdorf, about 4.2% of energy production in 33 month was lost due to inverter defects, but an additional 3.1% due to sporadic inverter malfunctions, that the owner did not know.

Inverter	Months of operation	Hardware failures per year				HW failures	HW failures per inverter operation year
		92	93	94	95	total	
PVWR 1500	37	0	0	0	0	0	**0.0**
PVWR 1800	144	0	3	5	3	11	**0.9**
Solcon 3300	39	0	0	0	0	0	**0.0**
Solcon 3400HE	67	1	1	4	0	6	**1.1**
TopClass 1800	22	0	0	0	0	0	**0.0**
TopClass 2500/6	16	0	0	0	0	0	**0.0**
TopClass 3000	64	1	2	1	0	4	**0.8**
TopClass 4000/6	47	0	0	0	1	1	**0.3**
SolarMax20	20	0	0	1	0	1	**0.6**
EcoPower20	19	0	0	5	0	5	**3.2**
Total	475	2	6	16	4	28	**0.7**

Table 3: Hardware defects for different inverter types

Table 3 shows hardware defects for different types of inverters. With some precaution due to the low sample size, you can see a certain tendency: New inverters coming from an experienced manufacturer, that have been manufactured for a few months at least before installation and that have no significant electronic parts but only a transformer for 50Hz providing galvanic separation on the AC side, seem to be more rugged and reliable than inverters using other principles. Future monitoring will show if this assumption is correct.

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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Conclusion

Performance and reliability of new PV inverters for grid connection are now much better than a few years ago. However, still more efforts are necessary to achieve the same standards common in energy technology.

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