New PV-Inverters from 2kW to 20kW for Grid-Connection: Results of extended Tests with single- and three-phase Units.

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ABSTRACT

Inverters are the most critical part of a grid-connected PV-installation. Operation of such inverters may affect other electrical equipment by overvoltage, harmonics and 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). Such problems have occurred in many grid-connected PV-installations in the last few years (sudden inverter failures or adverse effects on adjacent electrical equipment).

Since 1988 until early 1993 ISB's PV-laboratory has operated a PV-installation of 3kW and carried out a lot of tests with small inverters from 1kW to 3kW [1]. It has now moved to a new building with a PV-generator of 60kWp on top of the roof (see fig. 1). In this paper there is an overview of the possibilities of the new test site with 60kWp. In addition, latest test results and operating problems of some single-phased inverters and of the two medium-sized inverters of 20kW for three-phase-operation are presented.

1. ISB's new PV-Test-Installation (60kWp)

Voltages produced by the PV-generator can be selected between 30V (reduced power only) and 500V. Full power of 60kW is available at voltage levels between 100V and +/- 500V. With this new test site inverters of up to 60kW from any manufacturer can be tested under realistic conditions powered by a real PV-generator and not only a DC-power-supply. Therefore hidden problems (e.g. sporadic loss of maximum-power-tracking, a deficiency often observed with new inverter designs) can also be detected.

The PV-generator is divided into 60 arrays. Each array consists of 4 module strings in parallel. The number of modules per string is 6, 4, 3 or 2 (first number in array designation, see fig. 2). In the central PV switching room (see fig. 3), up to 4 arrays can be connected in series to form an array string and up to 4 array strings can be connected in parallel on several DC-busbars to obtain higher voltages and currents.

As there are quite high DC-voltages (up to 500V) and currents up to 100A in a test installation that is not wired always the same way, where unusual operating conditions may occur during the tests, care has been taken to ensure a maximum of safety.

1.1 DC-Side

All wiring on DC-Side is provided with a double insulation (operating voltage 600V to ground or 1kV between the wires, test voltage 3,5kV AC). Moreover, a very sensitive DC fault current switch for each array string was developed. It can detect a DC-difference current of 5mA and handle a current of up to 30A, much higher than nominal array string current of about 13A. In addition, a very good protection against lightning strokes and overvoltages is provided. More information about the lightning capturing rods developed especially for this project can be found in [2].

1.2 AC-Side

On the AC-side, there are also many measures to ensure safety and to detect dangerous operating conditions (e.g. islanding). The inverters under test can operate only if the following conditions are met:

- Voltage of all phases within given limits
- Frequency between 49.5Hz and 50.5Hz
- All AC voltages symmetrical
- No DC current in the phase lines
- No AC fault current detected

Fig. 1: New building of ISB's departement of electrical engineering with PV-generator of 60kWp on the roof (winter position).

Fig. 2: Top view of the 60 arrays of ISB's 60kWp PV-generator.
1.3 Test program
The following inverters will be tested for at least one year:
- SOLARMAX 20 (20kW, galvanic separation DC-AC), made by Sputnik AG, Switzerland
- ECOPOWER 20 (20kW, no galvanic separation DC-AC), made by Invertomatic AG, Switzerland
- SOLCON 3400 (3.4kW, single phase), made by Hardmeier, Switzerland
- TOP CLASS 4000 (4kW, single phase), made by ASP, Switzerland

Other inverters (e.g. PV-WR 5000 from SMA, Germany, POLYCON from Studer, Switzerland and others) can also be tested, if they are supplied free of charge for the tests and if funding for the assistants that perform the tests is continued.

1.4 Actual state of testing
Installation and commissioning of such a test installation is very complicated and takes a lot of time. The old test site was dismantled in February 1993. Due to delays and problems (especially with protection devices not on the DC but on the good old AC side!), operation of the two 20kW inverters for three phase operation started only on January 19, 1994 (SolarMax 20) and February 9, 1994 (EcoPower 20). Therefore continuous computer monitoring for the first system with SolarMax 20 was operational only in March 1994. As there were some initial problems with the second inverter that needed immediate consideration, only a few test results about these bigger inverters are available yet.

2. Test Results of Inverters for 1-phase Operation
Table 1 shows the most important specifications and the main test results of the single-phase inverters tested so far (definition of "European efficiency" in [1]).

2.1 New inverter SOLCON 3400
With the old test site of 3kW, a prototype of a new, improved SOLCON inverter (SOLCON 3400, 3.4kW) was tested. Compared to the older model SOLCON 3300 that was tested previously, efficiency at medium and high power levels could be increased by about 2% (see fig.4). RFI, a very weak point of early SOLCON models [1], was dramatically reduced and is now far below applicable standards on both AC- and DC-side (see fig.5 and fig.6). SOLCON 3400 had no problems with islanding under special load conditions (matched load) after loss of line voltage. Repeated tests with high telecontrol signal voltages (up to 20V, therefore higher than usual) caused no hardware defects (see fig.7).

![Graph showing efficiency of old inverter Solcon 3000 compared to efficiency of new Solcon 3400.](image-url)
In [3] there is an overview of the operating time and the number of hardware defects of all inverters monitored by ISB's PV-laboratory.

![Graph 5: Radio frequency interference on AC side for new Solcon 3400 (CISPR Conducted Pac = 350W).](image)

![Graph 6: Radio frequency interference on DC side for new Solcon 3400 (CISPR Conducted Pac = 900W).](image)

![Graph 7: Telecontrol signal sensitivity of Solcon 3400 at a line voltage of 220V and 250V and limits of admitted telecontrol signal voltage according to Swiss standard SEV 3600.1](image)

2.2 Reliability and Inverter defects

No hardware defects were encountered during the (relatively short) tests in ISB's PV-laboratory between summer 1992 and spring 1994. However, many inverters in PV-plants monitored in another project [3] by ISB's PV-group failed with hardware defects. Due to the limited number of sensors used in that project, the reason for these defects could not be determined.

On December 25, 1992, a prototype version of the new Solcon 3400 failed in a grid-connected PV-plant with 4.1kWp at Birg/Schilthorn (2600m), see fig. 8. According to the manufacturer the wiring on a printed circuit board was not large enough to handle the maximum current. The problem was cured in January 93. Fig. 9 shows a hardware defect at a PV-plant with 3.18kWp in Burgdorf equipped with a Top Class 3000 on April 11, 1993. The reason for this defect could not be determined, but the inverter had sporadic problems already a few days before [3]. In fig. 10, there is also a hardware defect at a PV-plant in Interlaken (8.9kWp) operating with 4 inverters PV-WR-1800 in master-slave configuration. Around 13:30, the master inverter failed, shutting down energy production of the whole plant. Around 16:50, the person in charge of the installation noticed the failure of the master inverter and changed the configuration, therefore energy production was resumed.
3. Test Results of Inverters for 3-phase Operation

3.1 SolarMax 20

This 20kW inverter was connected to the grid on Jan. 19, 1994 and operated without major problems so far. Only on March 23, 1994, automatic start in the morning did not take place and a manual start was necessary. No other problems were encountered so far. In fig.11 you can see irradiance G', DC power Pdc and AC power Pac on a fine and sunny day, March 27, 1994. Fig. 12 shows efficiency vs. DC input power as measured with ISB's automatic computer monitoring system (block diagram in [1], extended for three-phase measurements). The peak efficiency measured is about 91%. These results could not yet be confirmed by measurements with independent high precision instruments, therefore the diagram must be considered as provisional. Fig. 13 shows harmonic currents injected into grid by SolarMax 20 operating at Pac = 13.5kW. The harmonic currents at this power level are quite low. Only at a few frequencies they exceed the limits of EN60555-2, a standard established for smaller apparatus. These values are very good for a inverter of this size. Harmonics produced by a SolarMax 20 should therefore not cause any problems in practical use.

3.2 EcoPower 20

At first this inverter was connected to the 3 phase conductors L1, L2, L3 and the case to protective earth PE according to the recommendations of the manufacturer. In practical use the AC fault current detector of ISB's test installation was activated from time to time. Therefore several manual restarts a day were necessary. The reason for these events were sporadic quite high harmonic currents (many Amperes) in the phase lines and PE from time to time. To cure this, the case was connected to neutral N instead of PE, and PE was connected to N by means of two antiparallel power diodes. This measure alleviated the situation considerably, but did not yet resolve the problem completely. On March 28th the manufacturer succeeded to eliminate the sporadic high harmonic currents by adjustments on the control board. Since this modification the inverter works without shutdown problems. However, there are still harmonic currents >100mA in the N conductor in normal operation.

Due to the delay caused by this problem, no specific tests could take place by the end of March 94. The inverter with a rated power of 20kW is connected to the whole east side of our test generator (30kWp) with no overload problems and no hardware defects. Power limiting at rated power worked well so far. It has produced a lot of energy in February and March 94.

If an EcoPower is used with no AC fault current detector (usual case), the problems with harmonic currents are not affecting energy production of the inverter. However, in case of sporadic high harmonic currents applicable limits for harmonic currents or voltages at the connection point to the grid may be temporarily violated, if the control board is not modified as with ISB's inverter. As currents in PE should usually not occur in normal operation, but only in case of safety problems, the same change of the connection of N and PE is recommended.

4. Conclusion

ISB's new PV test site of 60kWp should be fully operational in summer 1994. It will increase the possibility for tests of PV systems and components considerably. The inverters SolarMax20, EcoPower 20, Solcon 3400 and the new Top Class 4000 will be tested thoroughly for at least one year. Hopefully test results will be as interesting as for the previous tests of smaller inverters [1]. ISB's PV-laboratory has also other interesting projects. It has examined measures for lightning and overvoltage protection of PV-systems [2], currently operates the highest grid-connected PV-plant (1152Wp) in the world at 3454m [3] and is active in development and tests of safety devices for PV-systems.

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 for any damage that might result from its use.

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