Islanding of Grid-connected PV Inverters: Test Circuits and Test Results

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1. Introduction

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. over-voltages, 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 electronic equipment).

With its PV test generator of 60 kWp and many other special equipment ISB's PV laboratory has carried out intensive tests of many grid connected PV inverters from 100 W to 20 kW. Table 1 (on next page) gives an overview over the main test results [1, 2, 3, 4].

2. Islanding

Many grid connected PV inverters are self-commutated, therefore they have a certain design inherent tendency for islanding. For safety reasons islanding is a major concern of many utilities. Islanding may be a problem and should be addressed, however its practical importance is sometimes overestimated. There are also other safety issues in grid connected PV systems that should be considered (e.g. problems caused by high DC voltage or possible arcs on the DC side).
In all the tests performed at ISB's PV laboratory since 1988 on many inverters, islanding ***never occurred after simply interrupting the connection to the mains***. The output voltage of the first inverters , which appeared on the Swiss market in the late eighties or early nineties and which had no RF filter on the AC side yet, dropped to 0 very quickly (within 1 or 2 cycles) after loss of line voltage. In newer inverters there are RF filters at the output to improve EMC behaviour. These filters represent a reactive load which tends to increase slightly the time until the cutoff of an inverter. Fig. 1 shows the output voltage of a newer inverter with an EMC filter after loss of line voltage under unmatched load conditions.

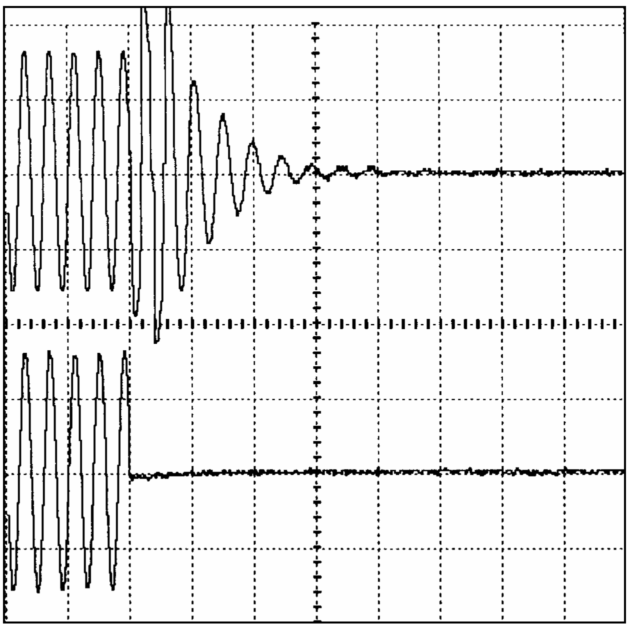


Fig. 1:

TopClass Grid II 4000/6, switch off *without matched load*, Pac ≈ 900W, no islanding.

Top: Output voltage of TopClass
Bottom: Line voltage
Vertical: 200V/div
Horizontal: 50ms/div

After loss of line voltage, a considerable increase of voltage occurs for about 2 cycles.

Type	Year of Test	S_N	V_{DC}	Euro-pean effi-ciency	Trans-former	Harm. content of current (<2kHz)	EMI AC	EMI DC	Sens. to tele-con-trol signal	Islan-ding
		[kVA]	[V]	[%]						
SI-3000	89	3.0	48	90	HF	0	-	-	0 1)	-/++ 3)
SOLCON	90/91	3.3	96	90	HF	+	- 1)	- -	+ 1)	-/++ 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	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	3.3	550	91.7	none	+	-/+ 1)	+	++	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	+	-/++ 2)	++	++
Edisun 200	95/96	0.18	64	90.7	HF	++	++	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	++	+	++
TCG III 2500/6	96	2.25	96	91.5	LF	+	+	++	++	++
TCG III 4000	96	3.5	96	91.9	LF	+	+	++	++	++

++	very good, meets the standard easily	*	3 phase units
+	good, meets the standard	1)	after ISB modification
0	satisfactory, meets the standard nearly	2)	with optional DC ring core choke
-	insufficient, doesn't meet the standard	3)	with new control software
- -	bad, doesn't meet the standard at all	4)	sufficient for module inverters (extension of DC wiring very small)
n.t.	not tested	5)	with 3-phase connection only

Table 1: Most important specifications and main test results of ISB's inverter tests from 1989 to 1996

2.1 Islanding under matched load conditions

To provoke islanding, it was always necessary to match a load at least to the real power of the inverter in order to bring the current between the inverter/load combination and the mains close to 0 before opening the connection switch. With self commutated inverters with RF-transformers, the power factor is usually close to 1, therefore operation with matched real power was already sufficient to provoke islanding in most cases, especially with designs from new, unexperienced manufacturers. Fig. 2 shows the test circuit used for the first islanding tests. Fig. 3 and 4 show islanding of two older inverters (SI-3000 and Solcon) after loss of line voltage.

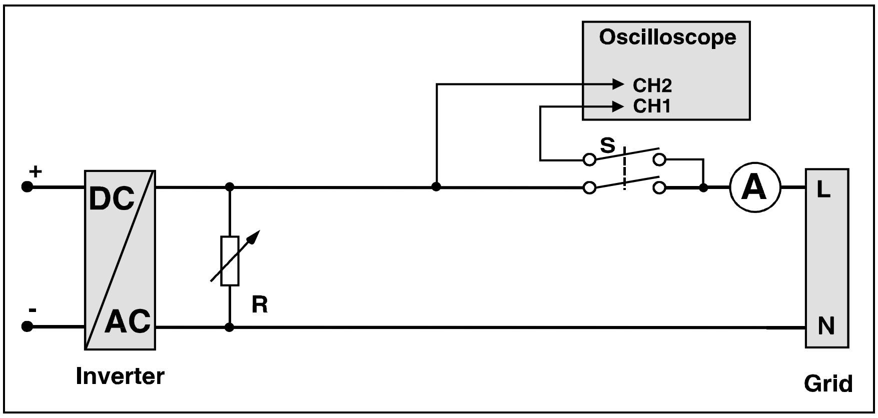


Fig. 2:
First test circuit for islanding tests with matched load.

Before opening the two switches, R is adjusted to bring the current through ammeter A to a minimum. CH1 is used to determine the switching moment.

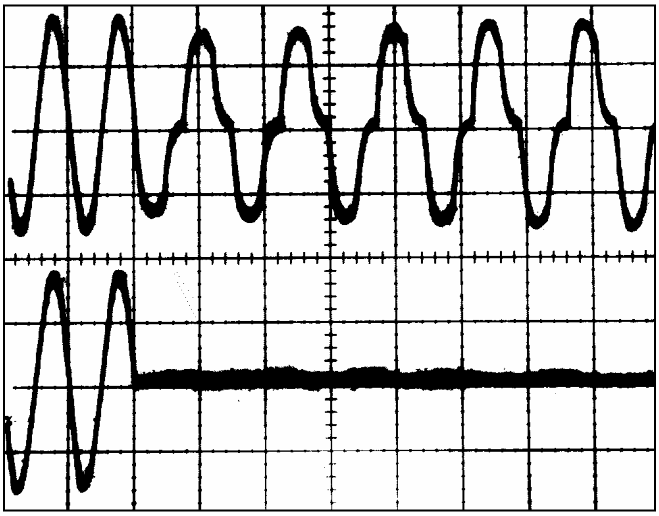


Fig. 3:

Islanding of SI3000.
Pac ≈ 420W, matched load, islanding up to 20s.

Top: Output voltage of SI3000
Bottom: Line voltage
Vertical: 200V/div
Horizontal: 20ms/div

Islanding frequency is considerably lower and THD of voltage higher than under normal operating conditions.

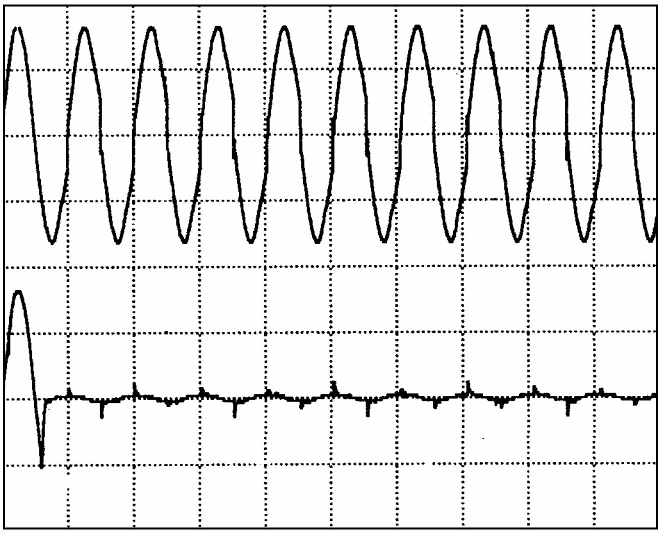


Fig. 4:

Islanding of Solcon (oldest model). Pac ≈ 300W, matched load.

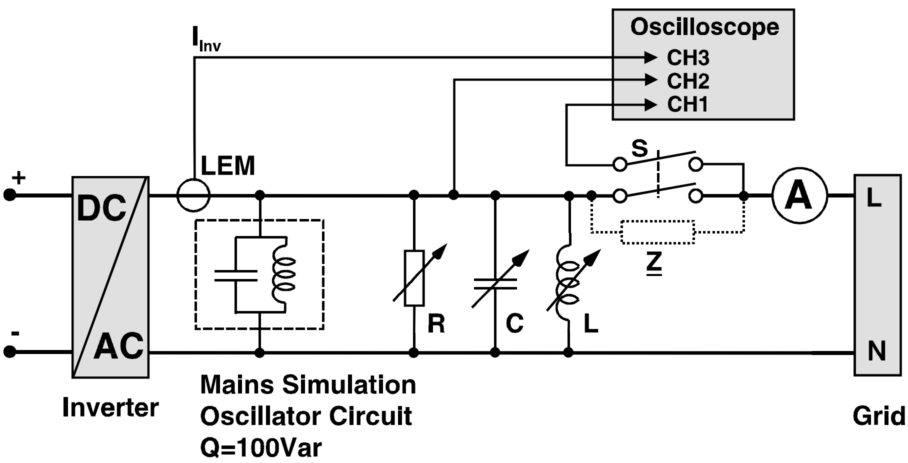
Top: Output voltage of Solcon
Bottom: Line voltage
Vertical: 200V/div
Horizontal: 20ms/div

Islanding could last up to **several hours**. Only a slight increase in voltage THD occurred in this case.

In most cases, such an islanding problem could be cured very quickly by the manufacturer. Inverters with a microprocessor control usually solved this problem by a software modification. For instance the stand alone frequency of the inverter can be chosen slightly higher or lower than the permitted frequency interval of the utility grid (in Europe: about 49.8 Hz to 50.2 Hz). By continuous monitoring of the output freqency by the microprocessor, an islanding condition can usually be detected easily within a reasonable time (less than 1 second). This frequency shifting scheme for islanding prevention is therefore quite easy to implement. To avoid problems in aereas with high inverter penetration and inverters from different manufacturers, the **direction of the frequency shift and the permissible frequency interval under islanding conditions** (outside the normal mains frequency interval) should be prescribed by an internal standard.

With the upcome of newer inverter designs with low frequency ring-core transformers, which proved to be more rugged in practical operation, a certain amount of reactive power is drawn from the grid. Therefore it became necessary to include means to compensate any reactive power consumption of the inverter to improve the matching to the load during the test. A new German proposal for islanding tests also introduced a mains simulation resonance circuit with an additional L and C consuming a reactive power of ±100 Var. These measures make detection of an islanding condition more difficult for the inverter under test. Therefore the test circuit for the islanding tests used at ISB's PV laboratory was modified to the circuit shown in Fig. 5. Fig. 6 and 7 shows islanding tests performed using this circuit with two newer inverters.

Fig. 5:
Improved test circuit for islanding tests.
R, L and C are adjusted until indication of ammeter A is at a minimum (ideal case: 0). For tests according to Swiss regulations Z is ∞.
For tests according to the new German proposal, Z and mains impedance $\underline{Z}_M$ combine to the total impedance required for the test.



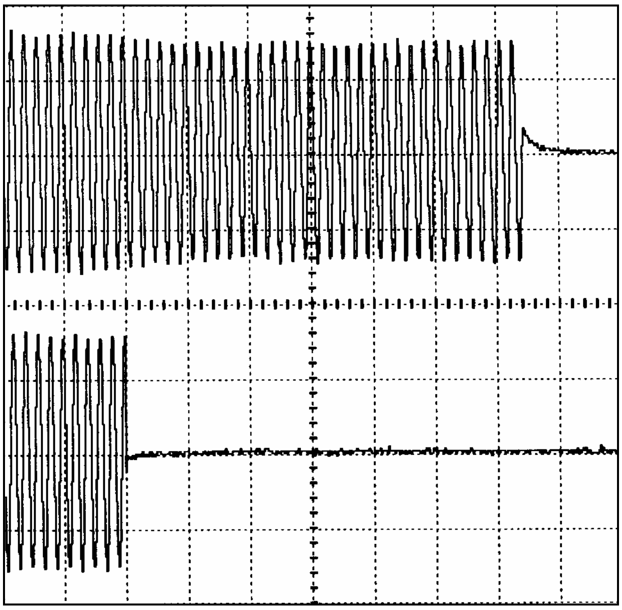


Fig. 6:

TopClass Grid II 4000/6, loss of line voltage *with matched load*, Pac ≈ 900W, no islanding.

Top: Output voltage of TopClass 4000
Bottom: Line voltage
Vertical: 200V/div
Horizontal: 100ms/div

About 650 ms after loss of line voltage the inverter shuts down. This time is considerably lower than the maximum time of 5 s permitted in the actual Swiss regulation.

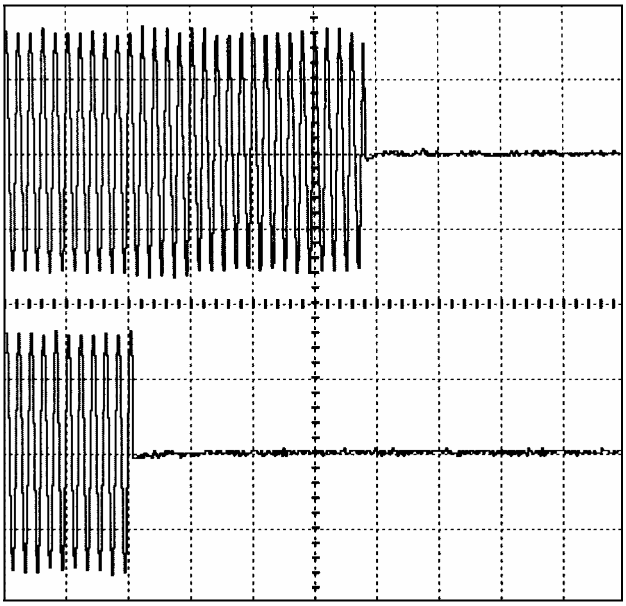


Fig. 7:

Solarmax S, loss of line voltage *with matched load*, Pac ≈ 800W, no islanding.

Top: Output voltage of Solarmax S
Bottom: Line voltage
Vertical: 200V/div
Horizontal: 100ms/div

About 380 ms after loss of line voltage the inverter shuts down. This time is considerably lower than the maximum time of 5 s permitted in the actual Swiss regulation

With the addition of an impedance Z accross the disconnect switch the test circuit of fig. 5 becomes equivalent to the more complicated test circuit according to a new proposal from Germany, but it is much easier to realize and to handle than the original German circuit described in fig. 8.
A three phase version of the test circuit of fig. 5 can be used for islanding tests of three phase inverters. Such tests were performed also with the two inverters of 20 kW. Solarmax 20 had no islanding under all load conditions. Ecopower 20 had sometimes problems with islanding at higher load levels (P_{AC}>14kW).

2.2 Short description of some applicable regulations for islanding prevention

Due to space limitations, only the ***key requirements*** can be given here. Of course there are other requirements like disconnection under over- und undervoltage conditions, permissible frequency intervals and so on.

In **Switzerland** a very open regulation is applied:
5 seconds after loss of line voltage the inverter must have switched off. This principal requirement must be fulfilled by single phase and three phase inverters.

In **Germany**, there are two different, more specific regulations for single phase inverters:

One possibility is the ***use of a special three phase relay*** inside the inverter, permitting connection to the mains only if all three phases are active. As in case of a utility disconnection all three phases are disabled simultaneously, this measure is usually sufficient to avoid islanding problems, especially if the inverter itself also has some built in properties to prevent islanding.

The other, more recent proposal is to ***monitor grid impedance to detect islanding***. The inverter must not connect the inverter if mains impedance Z_M >1.25 Ω . It must disconnnect the inverter within 5 seconds after a change ΔZ_M > 0.5 Ω or if Z_M >1.75 Ω. Line impedance monitoring can be done efficiently in strong grids like in cities, but might cause problems in weak rural grids. To test line impedance at regular intervals, the inverters must change the injected current into the grid at regular intervals, calculate the line impedance from these measurements, update the stored values from previous measurements and compare changes and absolute values against the figures given in the regulation. If the current of the inverter itself is used, line impedance monitoring can be done only when a sufficient amount of power is injected into the grid. Fig. 8 shows the proposed test circuit, fig. 9a , 9b and 9c how it can be converted into the much simpler circuit of fig. 5 by means of some network theory (use of equivalent voltage source).

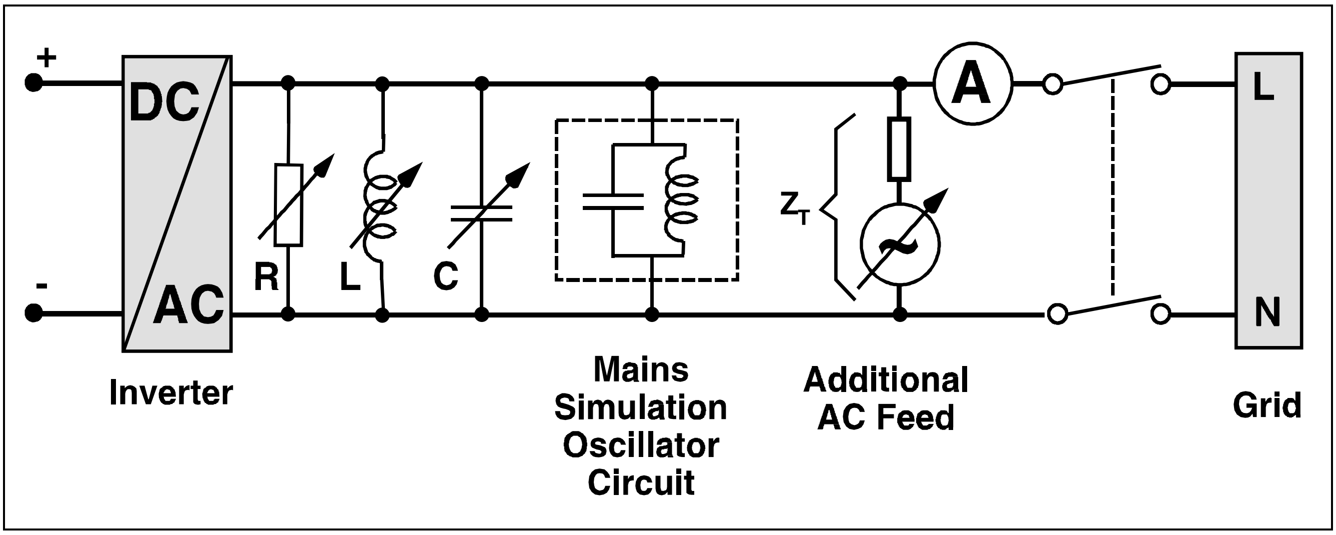


Fig. 8: Circuit to test the automatic isolation under islanding conditions according to new German regulation. The mains simulation oscillator circuit consists of a L and a C consuming Q = ± 100 Var . Additional AC feed: 30% of inverter power.

Fig. 9:
The mains is represented by a voltage source $\underline{V}_M$ in series with mains impedance $\underline{Z}_M$.

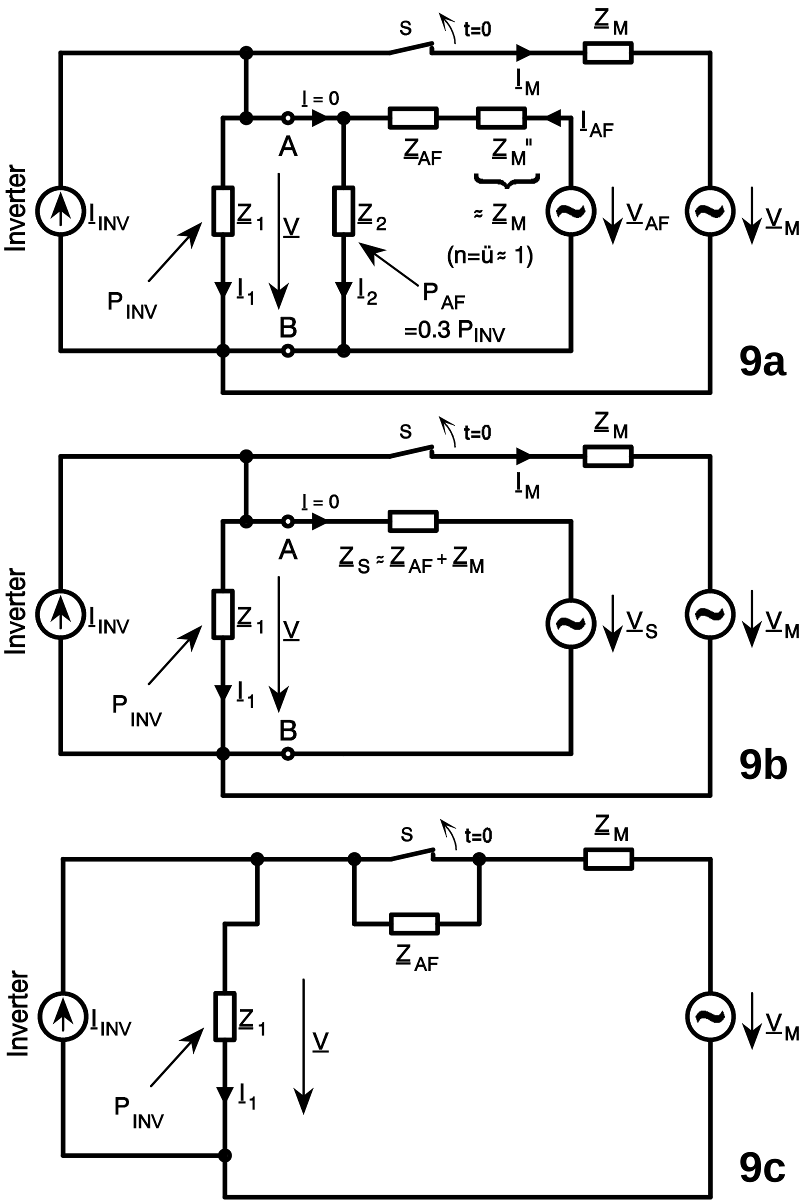
Total parallel impedance is split into $\underline{Z}_1$ taking real power P_{INV} from the inverter and $\underline{Z}_2$ taking the power from the additional AC feed **AF** (usually connected at the same point by means of an adjustable transformer with $\underline{Z}_{AF}$). Mains impedance on the secondary side of this transformer is $\underline{Z}_M$'' $\approx \underline{Z}_M$, as n $\approx$ 1.

When the **matching condition** is met, $\mathbf{\underline{I}_M}$ **and** $\mathbf{\underline{I}}$ **are 0**.

To get circuit **9b**, $\underline{V}_{AF}$, $\underline{Z}_{AF}$, $\underline{Z}_M$''and $\underline{Z}_2$ are converted to an equivalent voltage source $\underline{V}_S$ in series with $\underline{Z}_S \approx \underline{Z}_{AF}+\underline{Z}_M$. ($Z_2 >> |\underline{Z}_{AF}+\underline{Z}_M''|$).

As $\mathbf{\underline{I}_M}$ and $\mathbf{\underline{I}}$ are **0**, $\mathbf{\underline{V}_S = \underline{V} = \underline{V}_M}$. When switch S is open, the mains is still connected via $\underline{Z}_S \approx \underline{Z}_{AF} + \underline{Z}_M$ instead of only $\underline{Z}_M$.

When switch S is open, circuit 9b is equivalent to the circuit of fig. **9c**. This is the much simpler circuit of fig. 5 with $\underline{Z} < \infty$. Opening switch S creates an impedance step $\underline{Z}_{AF}$.



2.3 Measuring principle of two inverters with grid impedance monitoring

Fig. 10:

Grid impedance measuring of SMA SWR700, Pac ≈ 130W

Curve 1: Output voltage of SWR700 (100V/div)
Curve 2: Output Current of SWR700 (2A/div)
Horizontal: 2ms/div

A current peak close to the zero crossing of the line voltage is used.

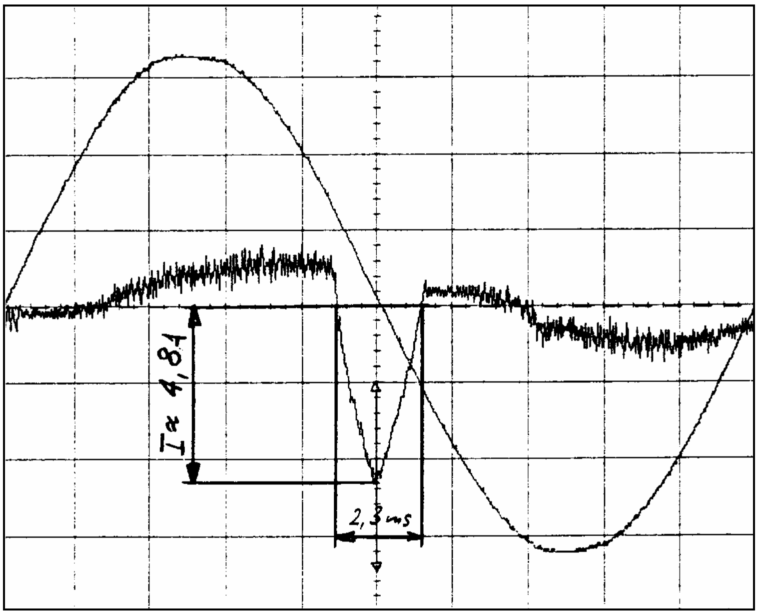


Fig. 11:

Grid impedance measuring of Siemens SPN1000

Curve 1: Output voltage of SPN1000 (100V/div)
Curve 2: Output Current of SPN1000 (2A/div)
Horizontal: 10ms/div

Injection of current (and power!) is interrupted for about 2.5 cycles. To get a big difference, a strong current pulse is used afterwards to measure line impedance.

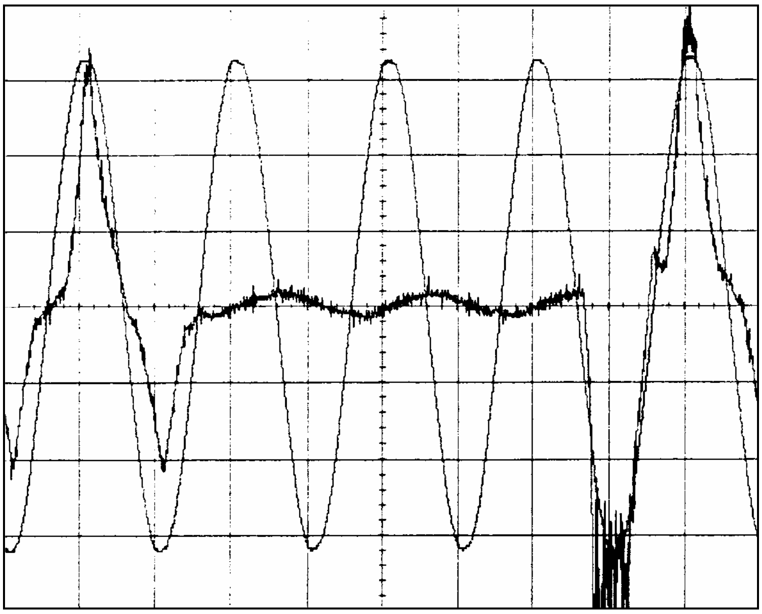
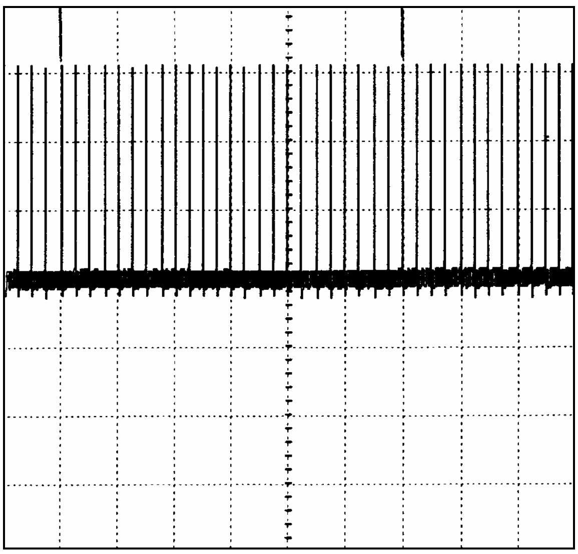


Fig. 12:

Grid impedance measuring of Siemens SPN1000.

1 pulse per measuring cycle
Horizontal: 10s/div

To get some immunity to noise on the mains affecting measurement accuracy, a measurement is taken every 2.5 s enabling confirmation of a value out of range by a second measurement before disconnecting the inverter.



3. Conclusions

A simple method to detect islanding is to choose the free running frequency of the inverter outside of the frequency interval of the utility grid. By continuous monitoring of the inverter output freqency by the microprocessor, an islanding condition can be detected easily. This frequency shifting scheme is not affected by weak grids with relative high impedances in rural areas and does not require a minimum power level to be implemented practically. This method has been adopted by many manufacturers yet and is performing well in the field. However, if this scheme is used, it is essential to standardize the direction of the frequency shift and the permissible frequency interval under islanding conditions (outside the normal mains frequency interval) in order to avoid problems in areas with high inverter penetration and inverters from different manufacturers.

Continuous line impedance monitoring is certainly a new and interesting approach to the problem of islanding prevention. However, it creates also some problems:

- If the operating current of the inverter itself is used, a certain mimimum current (or power) is required to get a detectable impedance signal. Therefore, the test procedure used in Germany requires tests only at 30% and 100% of rated power. However, if islanding is a problem, it is not only dangerous at these power levels, but also at lower power levels and should be prevented also there.
- Continous current variations of inverters in order to measure mains impedance create additional noise (voltage fluctuations) on the mains which is certainly not desirable and reduces power quality.
- At locations with weak grids or frequent voltage fluctuations, stable operation of inverters with continuous line impedance monitoring may be affected or even be not possible.
- In cities with very large transformers, remaining loads in a disconnected part of the grid might constitute a total impedance lower than 0.5Ω preventing a detection of an islanding condition. This of course would only be a problem with a very large penetration of grid connected PV systems, which is not the case yet in the near future.

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