# OPERATING PROPERTIES OF HYBRID INVERTERS AND POWER FLOW REGULATORS

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## ABSTRACT

*The paper defines the basic problems of the operation of hybrid photovoltaic systems up to 10 kWp with accumulation – the conditions for elimination of overflows into the distribution network are defined and problems related to the transitions between interconnected and islanded operation mode are identified. At the Brno University of Technology, tests of DC/AC inverters were performed, focusing on the reaction times of the inverters. The results show significant differences for each type of inverter. The results obtained were analyzed and used for the subsequent design of a hybrid photovoltaic system with accumulation.*

## INTRODUCTION

Use of power flow regulators has been increased due to changes in the connection and operating conditions of micro-sources (installation up to 10 kW) in Czech Republic, one of the basic changes is the requirement to minimize the energy flow to the power grid. In the Energy Regulatory Office Decree No. 16/2016 in § 16, section 2b, it is stated that it is required: *technical solution of micro-source that avoids the supply of electricity to the distribution system at the point of connection, except for short-term overflows of electricity into the distribution system which serve to react a restricting device but which does not increase the voltage at the connection point* [1].

Due to the nature of the source (variable production) and the nature of the electricity consumption (the variable power consumption of the appliances in the building) it is not possible to simply ensure that there is a balance between current production and consumption at all times.

The disproportion between the production and consumption of electricity in an object leads to the supply of energy to the grid, that the actual energy output of the power source is higher than the sum of the instantaneous power consumption of the appliance in the building. The possibilities of reducing the supply of electricity to the grid to the minimum can be as follows:

- Power source performance reduction – cooperation between the inverter and the measuring module at the transfer point or use of hybrid inverter with accumulation.
- Increasing the load (energy accumulation) – usually the accumulation of electric energy in the form of heat usually by using water heating systems or by using batteries (direct storage of electricity) [2].

The DC/AC inverters response time depends on the use of the algorithm and the mode of measurement of the active power. Voltage and current measurements can be made at the input connection terminals (AC IN) of the hybrid inverter that means at the point of connection to the electricity revenue meter. In this case, an eventual overflow of active power evaluates the inverter using internal algorithms. The second option is to use an external measuring module or a smart meter that is connected to the inverter via a communication interface and sends the current measured value at the connection point or directly required active power of the inverter. Use an external measurement module degrades the inverter's response time and may cause undesirable oscillation of the active power at the transfer site.

The power flow regulator evaluates measured currents and voltages. The actual value of active power and its direction is calculated from the sampled values. The active power value enters the proportional-integration controller, which subsequently switches the individual loads according to the set algorithm. The following ways of load switching have the impact on voltage quality at the point of common coupling (PCC):

- Cascade load switching using coil relays does not affect the grid voltage quality significantly if the switched load is of reasonable power. It is important, that the power of the loads is rationally distributed between the relay outputs, to prevent high step changes and to use the whole potential of cascade switching [3].
- Dynamic load switching using SSR (Solid State Relay) with ZCS (Zero Crossing Switching). Using pulse width regulation can be the load power virtually controlled in the range 0-100 %. Instantaneous load power varies between zero and maximum power and the average load power is dependent on the duty cycle of switching element. The minimal time that a ZCS SSR can operate depends on the frequency of the supply voltage and for 50 Hz is equal to one half-period (1xHP = 10 ms). Rapid load switching can lead to a significant increase in the short-term flicker and flashing light sources as a result [3].
- Dynamic load switching using triacs. Considering switching of the load even faster, waveform shape of the load supply voltage within period has to be changed commonly at leading edge using triacs. Two kinds of disturbances are related to harmonic distortion exhibiting in range to $40^{th}$ harmonic order and high frequency conducted differential disturbances due to fast switching edges [3].

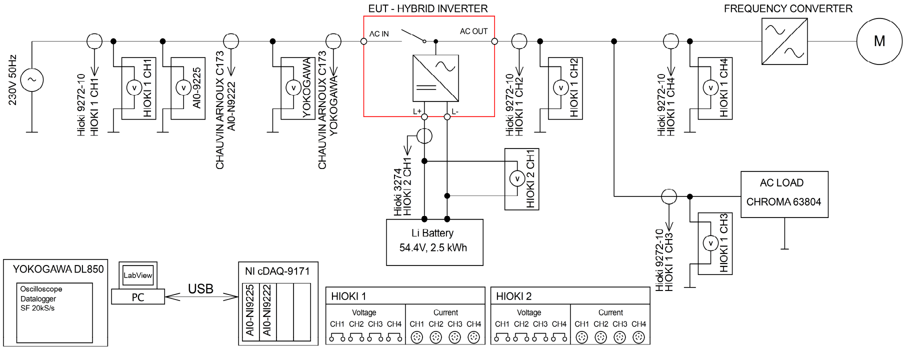


Fig. 1 Wiring diagram for hybrid inverters testing

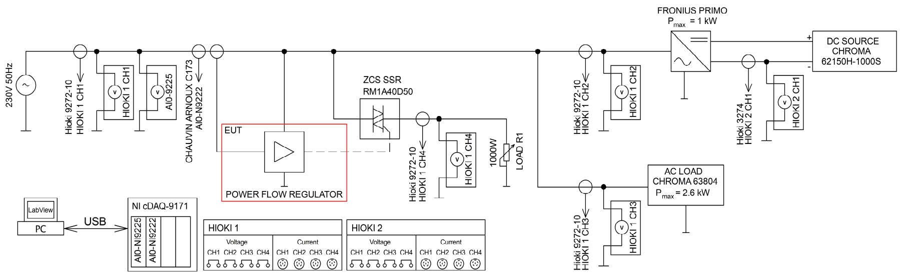


Fig. 2 Wiring diagram for power flow regulators testing

# EXPERIMENT SETUP

In Renewable Energy Sources Laboratory (RESLAB) at Brno University of Technology were realized operating tests of hybrid inverters and power flow regulators - the tests were aimed at verification of their declared functions and their influence on the electricity meter metering (the experiment diagrams in Fig. 1 and Fig. 2). The benefits of the analysis are important information about the operating characteristics of hybrid inverters and power flow regulators. Based on these information were defined the conditions for the use of these devices. Based on the results of the tested inverters, the design concept of the hybrid system for DC coupling was designed and verified, while respecting the operational requirements for the transition between network and island operation, including a condition to avoid energy overflows to the distribution network. An important output of the measurement of the performance characteristics of the power flow regulators was the actual amount of energy supplied to the grid.

## Testing Conditions

Programmable RLC load Chroma 63804 with variable load diagram (Fig. 3) was used for testing the reaction time of hybrid inverters.

In power flow regulators tests was used DC source Chroma 62150H-1000S to simulate the output of photovoltaic (PV) panels. It was controlled by personal computer, with the software Chroma Soft Panel simulating the PV panels with $P_{mpp}$ = 1 kWp according to the irradiance curve (Fig. 4 – blue curve). Programmable RLC load Chroma 63804 simulated the power consumption with the defined load diagram (Fig. 4 – green curve). Tested power flow regulator switched the 1 kW resistive load using ZCS-SSR.

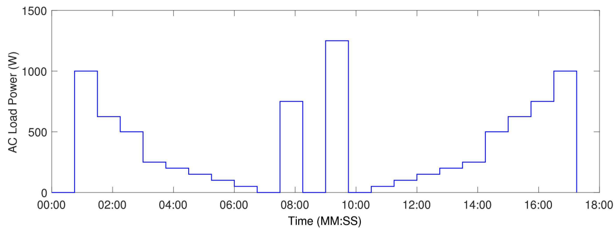


Fig. 3 Hybrid inverter AC load test sequence

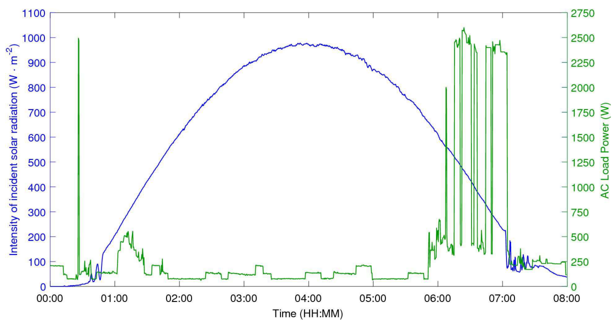


Fig. 4 Power flow regulators AC load and PV source test sequence

Two synchronized four-channel power analyzers HIOKI 3390-10 were used to measure individual energy flows. The layout of the measurement points indicates the wiring diagram of the measurement task (Fig. 1 and Fig. 2). Due to the fact that the analyzers integrate the amount of electrical energy with a measuring window length of 50 ms, the amount of energy (with respect to the control principle by ZCS SSR relay) is not recorded correctly. For accurate measurement of the energy flow at the point of connection of the simulated object to the distribution system was measurement made using by a virtual power meter. Virtual power meter was realized by National Instruments measuring cards for measuring voltage and current waveforms. The active energy is measured in real time in a measuring window of one

half-period of the network frequency (10 ms) and the measuring window is synchronized with the half-wavelength supply voltage. In this way, the actually collected ($E_{rW+}$) and supplied ($E_{rW-}$) active electrical energy indexed in the energy registers and including the course of half-time values of active power [4]. To record transient phenomena of hybrid inverters was used oscilloscope Yokogawa DL850 with sampling frequency 20 kS/s.
Four different types of hybrid inverters were tested during experiments. The hybrid inverters were tested for control stability and reaction time when the output is connected to variable load. Also the energy fed to grid during load decrease was measured. Fourth inverter was controlled using external measuring module connected with RS485 interface and MODBUS protocol.

## Data Processing and Evaluation

Data measured with virtual half-period power meter were evaluated using Matlab script. The script allowed to set variable length integration time window and aggregate the energy using the given integration time window to see the effect of SSR switched load at the electricity meter function. In the evaluation were used multiples of half-period (NxHP). For the 50 Hz grid were the window lengths 1xHP = 10 ms, 2xHP = 20 ms, 20xHP = 200 ms and 100xHP = 1000 ms. The common integration window of the electricity revenue meters are 200 and 1000 ms.

# RESULTS

## Hybrid Inverters Tests

The results of each tested inverter AC IN response (black curve) to variable load change at AC OUT (red curve) are shown in Fig. 5 – Fig. 7. In ideal state, the hybrid inverter should be capable to cover the increased load at AC OUT by the energy stored in battery. As can be seen from the results, inverter #1 (Fig. 5) and #2 (Fig. 6) have problem with the load step changes and power is fed to the grid when the load is disconnected. Control algorithms cause undesirable power oscillations at the PCC with response time in range of 400 – 600 ms and oscillations duration in range of 20 – 45 s for inverters #1 and #2. The good design and quality of control algorithm was observed in operation of inverter #3 where the response time to load change was under 10 ms. In the Fig. 7 was no power fed to the grid and no power oscillation were observed. The worst results were obtained from the test of inverter #4. The use of external control module resulted in reaction time about 100 s with intensive oscillation (see Fig. 8) after the load was disconnected (approx. time 1450 s). The result for the inverter #4 also show the average power calculated using variable integration window length.

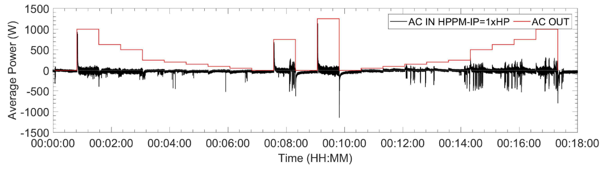

Fig. 5 Inverter #1 – AC IN power with variable AC OUT load profile

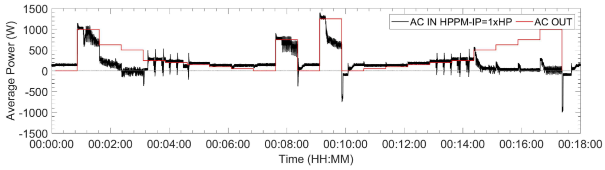

Fig. 6 Inverter #2 – AC IN power with variable AC OUT load profile

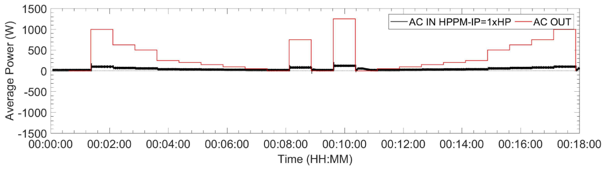

Fig. 7 Inverter #3 – AC IN power with variable AC OUT load profile

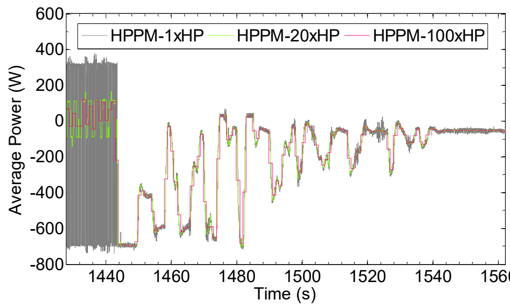

Fig. 8 Reaction time of inverter #4 to load disconnection (power in PCC) – external control module

## Power Flow Regulators Tests

The results of power flow regulators tests are in Fig. 9 – Fig. 11. It can be seen, that the SSR switched load affects the average power (and energy) measured at the PCC according to the length of integration time window. All tested power flow regulators are using the grid as the short-term accumulation device. The power is changing its direction and the load switching uses the weakness of measuring algorithm of electricity revenue meter (integration time window of 200 ms or 1000 ms). Results of energy with respect to the variable time window length are shown in Tab. 1 – Tab. 3. For the power flow regulator #1 was assembled the overview of energy flows in the test system (Fig. 12).

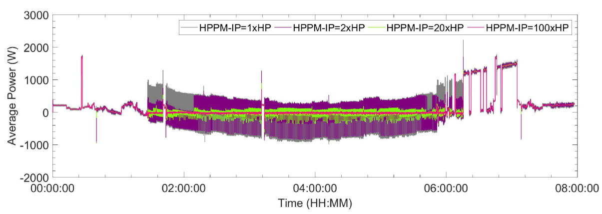

Fig. 9 Power flow regulator 1 – active power flow in PCC considering variable integration window length

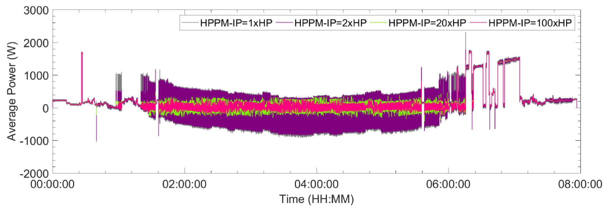


Fig. 10 Power flow regulator 2 – active power flow in PCC considering variable integration window length

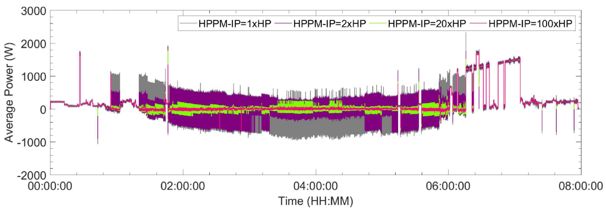


Fig. 11 Power flow regulator #3 – active power flow in PCC considering variable integration window length

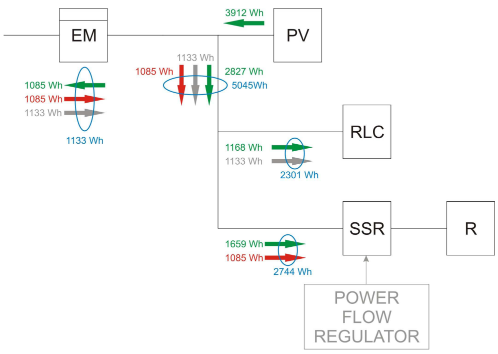


Fig. 12 Energy flows in experiment with regulator #1

The results in Tab. 1 – Tab. 3 show the amount of energy that the electricity revenue meter with a measurement period of 100 HP "did not measure". Compared to a virtual power meter, the difference in the amount of measured electrical energy can be up to $\varepsilon_{rW-}$ = 95% (network supply) and up to $\varepsilon_{rW+}$ = 44% (consumption). The results of the tests indicate the need for changes in the measurement of electrical energy – current types of electricity revenue meters (their measuring algorithms) are not designed to rapid changes between supply and consumption at the point of connection.

Tab. 1 Regulator #1 results Half-period power meter with variable integration (NxHP)

| | 1xHP | 2xHP | 20xHP | 100xHP |
|---|---|---|---|---|
| $E_{rW+}$ (Wh) | 2218.6 | 1625.5 | 1299.9 | 1249.9 |
| $E_{rW-}$ (Wh) | -1085.4 | -492.4 | -166.8 | -116.8 |
| $\lvert E_{rW+}\rvert - \lvert E_{rW-}\rvert$ (Wh) | 1133.2 | 1133.2 | 1133.1 | 1133.1 |
| $\varepsilon_{rW+}$ (%) | 0 | -26.7 | -41.4 | -43.7 |
| $\varepsilon_{rW-}$ (%) | 0 | -54.6 | -84.7 | -89.3 |

Tab. 2 Regulator #2 results Half-period power meter with variable integration (NxHP)

| | 1xHP | 2xHP | 20xHP | 100xHP |
|---|---|---|---|---|
| $E_{rW+}$ (Wh) | 2426.7 | 2094.8 | 1575.9 | 1526.3 |
| $E_{rW-}$ (Wh) | -998.8 | -667.0 | -148.1 | -98.4 |
| $\lvert E_{rW+}\rvert - \lvert E_{rW-}\rvert$ (Wh) | 1427.9 | 1427.9 | 1427.9 | 1427.9 |
| $\varepsilon_{rW+}$ (%) | 0 | -13.7 | -35.1 | -37.1 |
| $\varepsilon_{rW-}$ (%) | 0 | -33.2 | -85.2 | -90.2 |

Tab. 3 Regulator #3 results Half-period power meter with variable integration (NxHP)

| | 1xHP | 2xHP | 20xHP | 100xHP |
|---|---|---|---|---|
| $E_{rW+}$ (Wh) | 2330.1 | 1818.5 | 1455.4 | 1331.9 |
| $E_{rW-}$ (Wh) | -1055.4 | -543.8 | -180.8 | -57.2 |
| $\lvert E_{rW+}\rvert - \lvert E_{rW-}\rvert$ (Wh) | 1274.7 | 1274.7 | 1274.7 | 1274.7 |
| $\varepsilon_{rW+}$ (%) | 0 | -22.0 | -37.5 | -42.8 |
| $\varepsilon_{rW-}$ (%) | 0 | -48.5 | -82.9 | -94.6 |

## CONCLUSIONS

Aim of the paper was to present the results obtained from the hybrid inverter and power flow regulators test system. The results have shown the importance of correct power and energy measurement in connection with hybrid renewable energy system and power flow regulators. Present static electricity meters have significant weakness in metering algorithm that is given by the used simplifications in their design.
The reaction time of hybrid inverters to load changes depends on the quality of implemented control algorithms and the location of power measuring point (internal/external).

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## REFERENCES

[1] Energy Regulatory Office, “Decree No.16/2016 on conditions for connection to the electricity grid”, 2016, Czech Republic
[2] P. Mastný, J. Morávek, M. Vrána, J. Drápela, 2017, “Operating characteristics of power flow controller in combination with RES”, *Proceedings ČK CIRED 2017 Conference*, Tábor, vol. 1, 1-9
[3] J. Morávek, J. Drápela, V. Wasserbauer, P. Mastný, 2016, “Power Quality Issues Related to Power Flow Control in Systems with Renewable Energy Micro Sources”, *Proceedings of the 2016 17th International Scientific Conference on Electric Power Engineering*, Prague, 283-288
[4] J. Novotný, J. Drápela, D. Topolánek, 2016, “Frequency response of revenue meters in measured active energy”. *Proceedings of the 2016 IEEE 17th International Conference on Harmonics and Quality of Power (ICHQP),* Belo Horizonte, Brazil, 524-529.
[5] Commission Regulation (EU) 2016/631 of 14 April 2016 establishing a network code on requirements for grid connection of generators, 2016
[6] EN 50160:2010, “Voltage characteristics of electricity supplied by public electricity networks”