5.3 BALANCE OF SYSTEM COMPONENTS

PERFORMANCE OF RECENT INVERTER SYSTEMS UNDER PARTIAL SHADING CONDITIONS

RESULTS FROM SIDE-BY-SIDE COMPARISON IN A FIELD TEST

Ralph Lingel • Thomas Nordmann • Thomas Vontobel
lingel@tnc.ch • nordmann@tnc.ch • vontobel@tnc.ch
TNC Consulting AG
General Wille-Strasse 59 • 8706 Feldmeilen • CH – Switzerland
www.tnc.ch • P: +41 44 991 5577

ABSTRACT: Three common but fundamentally different inverter concepts are investigated under two types of partial shading conditions. One string inverter stystem, one microinverter system and one inverter system with power optimizers are installed in a side-by-side configuration at an existing PV plant. During summer one third of the modules experiences a similar shading situation due to self-shading. During winter season the whole plant is shaded heterogeneously by several objects in the vicinity. Due to the string design and the homogeneous shading in summer no increase in yield could be measured for the two decentralized inverter systems compared to the string inverter system. The system with power optimizers achieves equal performance values compared to the string inverter. The microinverter system with a lower inverter efficiency achieves lower yield values of -10 % on month base compared to the string inverter. Under heterogeneous shading conditions in winter both decentralized inverter systems can achieve significantly higher yields compared to string inverters. On a month base + 92 % for the system with power optimizers and +57 % for the microinverter system were measured.

Keywords: PV systems, partial shading, power optimizers, microinverter

1 PURPOSE OF THE WORK

Partial shading on PV systems with string inverters can cause significant reduction in yield. Manufacturers of decentralized inverter systems, such as inverters with power optimizers and microinverters hold out the prospect of an increase in yield of more than 25 %. There is little operational experience and data from PV plants published comparing these fundamentally different inverter systems under the same shading conditions. In this work three different inverter concepts are investigated under two different types of partial shading at a "real-life" PV-plant.

2 INVERTER CONCEPTS TESTED

Three fundamentally different inverter concepts are investigated. The string inverter system characterizes a central DC/AC conversion together with MPP-tracking on string level. Partial shading within one string affects the performance of all other modules in this string. With microinverters DC/AC conversion and MPP-tracking takes place per PV module. Inverters with power optimizers have a MPP-tracking per module (DC/DC) and a central DC/AC conversion.

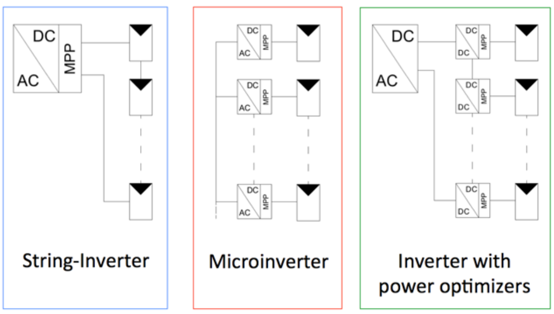

Fig. 1: Three different inverter Systems

3 PV-PLANT AND SHADING SITUATION

The tests are carried out at an existing PV testing plant near Zurich, which was built in 1998. The plant consists of 45 modules (210 W_p) arranged in three rows and has a nominal power 9.5 kW_p (Fig. 2).

Fig. 2: Testing plant: partial shading in January

During winter season the plant is affected by shading caused by houses and trees in the vicinity (Fig. 2 & 3). Using simulation tools (Meteonorm; PV*SOL) the calculated reduction of irradiation compared to an open horizon is 48% in December for the whole plant with a maximum of 78 % for the module at the most shaded position.

Fig. 3: houses and trees in the southern vicinity of the plant

Due to the characteristic zig-zag shape of the PV plant the undermost row experiences shading caused by the rows above during summer months (Fig. 4). The calculated reduction of irradiation onto this row is 20 % in June compared to open horizon. The shading losses for the whole plant are 15% on annual base.

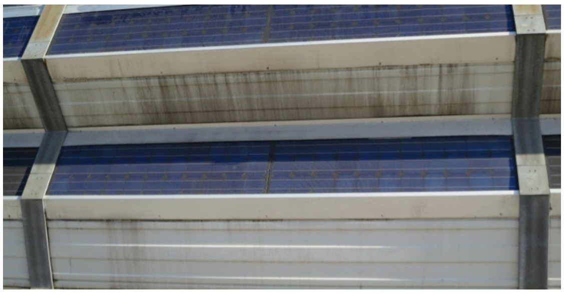

Fig. 4: Shadow on undermost module during summer

4 IMPLEMENTATION AND MONITORING

The inverter with power optimizers (15x) and the string inverter (2 MPP trackers) were installed in February 2014 together with the measurement equipment.
To ensure that all three inverter systems experience comparable shading conditions the modules are assigned in a "checkered" manner to the inverters (Fig. 4 & 5).
The modules assigned to the string inverter (blue) are distributed to two strings. The string inverter has a global maximum power point tracking which is useful especially under shading conditions. The modules of the upper rows are connected to the first MPP-tracker and the modules of the undermost row to the second MPP-tracker.
The 15 microinverters were installed in March 2015.

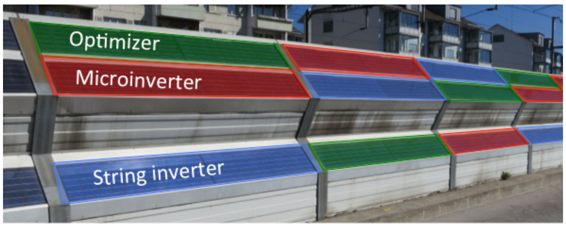

Fig. 4: Allocation of modules to the inverter systems

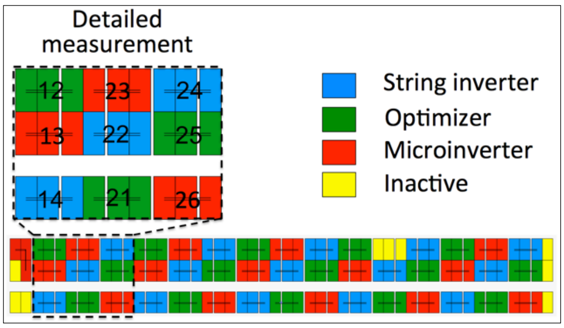

Fig. 5: Plant overview and modules with detailed measurement

The plant is equipped with precise measurement equipment, recording DC and AC values of the plant. Beside inverter and string values the most shaded modules "12" to "26" are monitored in detail. Two pyranometers measure irradiation in horizontal and module plane. Module and ambient temperature is also collected. The values are recorded on a minute base.

5 RESULTS

Preliminary results comparing operational behavior of the string inverter and the optimizer system were presented in [1]. With the installation of microinverters in Q1/2015 three fundamentally different inverter concepts can be compared under partial shading conditions. In June 2016 one year of operation and measurement has been completed. In the following chapters operational data of all three systems are presented and analyzed.

5.1 OBSERVING SINGLE DAYS

Figure 6 shows the DC-power output of three modules with string inverter on a sunny day in July (10/07/15). The effect of shading onto the module of the undermost row "14" between 8:00 h and 11:00 h is clearly visible. Figure 7 illustrates the normalized AC-power output of the three inverter systems for the same day. No difference in performance can be seen between the three systems for the time period when the undermost row is shaded. The string design leads to similar shading/irradiation conditions within the two strings and therefore there is no advantage for the two decentralized inverter systems. Around midday it can be seen that the string inverter and the optimizer system show a similar performance whereas the microinverters show a slightly lower power output (-5 %). This correlates well with the nominal inverter efficiencies: string inverter: 96 %; optimizer system: 96 %, microinverter: 92 %.

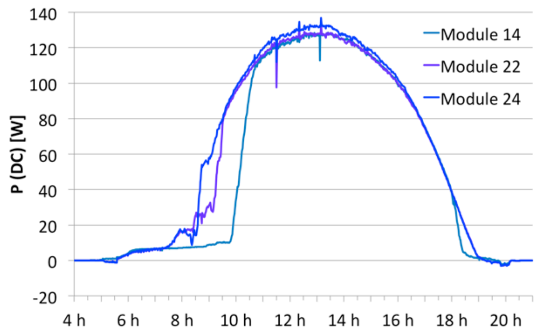

Fig. 6: DC-power of three modules with string inverter on a sunny day in July

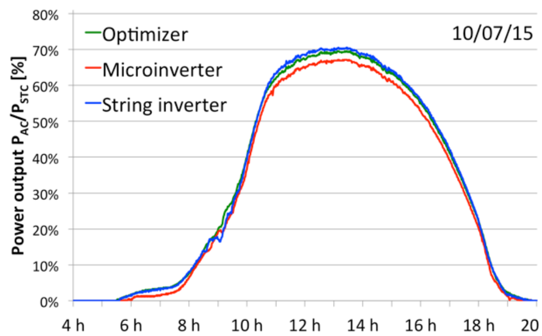

Fig. 7: Normalized AC-power output of the three inverter systems on a sunny day in July

Figure 8 shows the DC-power output of the three modules with string inverter on a sunny day in October. It can be seen that the power output of the modules breaks down according to their position in the PV-plant and the course of the shadows caused by the objects in the vicinity. The power outputs even reach negative values. This can be explained by the voltage drop at the bypass diodes of the modules.

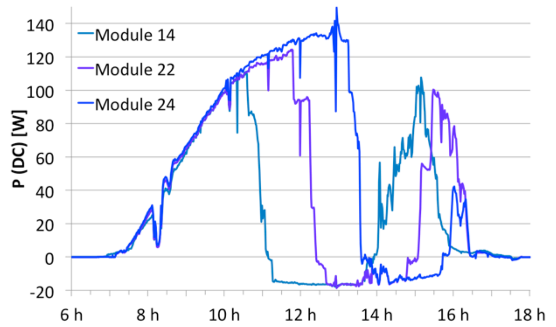

Fig. 8: DC-power of three modules with string inverter on a sunny day in October

The PV-plant experiences most severe shadow during December and January when sun is low on the horizon. Figure 9 illustrates the normalized AC-power output of the three inverter systems on 24/12/2015. Due to the heterogeneous shading situation, both, the optimizer system and the microinverters show a significantly higher power output compared to the string inverter. The difference in power indicates that not only the voltage drop of the bypass diodes causes this lower performance. It can be assumed that due to the great differences of irradiation conditions within the strings, most modules operate outside their optimum operating point. For this day the yield of the optimizer system is 133 % higher compared to the string inverter. The microinverter system achieves a 110 % higher yield.

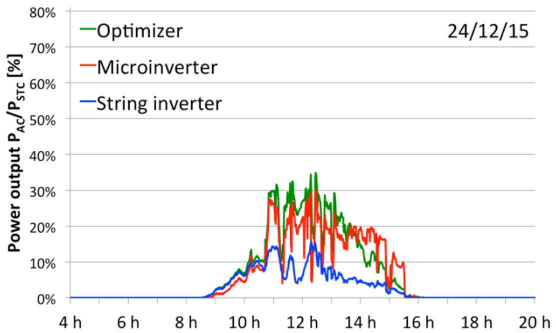

Fig. 9: Normalized AC-power output of the three inverter systems on a sunny day in December

5.2 SEASONAL CHANGE OF SHADING CONDITION AND ITS IMPACT ON PERFORMANCE RATIO

Figure 10 shows the final yield plotted versus the reference yield (irradiation) for the three systems in July 2015. It can be seen that irrespective of irradiation the string inverter and the optimizer system perform in a very similar way. The microinverters show a slightly lower final yield also irrespectively of daily irradiation values. This indicates the lower inverter efficiency of this system.

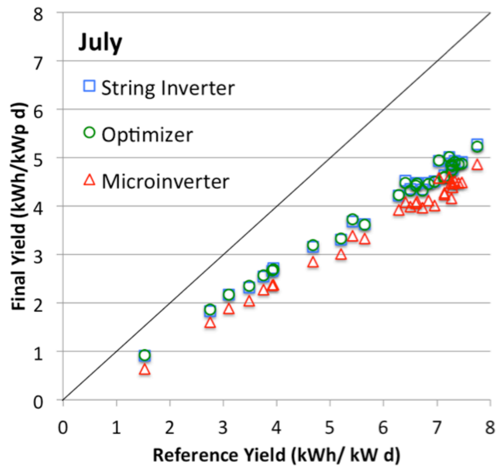

Fig. 10: Final yield vs. reference yield for the three inverter systems in July 2015

Figure 11 shows the final yield plotted versus the reference yield for the three systems in December 2015. The optimizer system shows the highest final yield values both for high and low irradiation values. On sunny days now the microinverter system shows a significantly higher performance compared to the string inverter. Under the very heterogeneous irradiation situation at this time of the year the advantage of decentralized MPP-tracking is overcompensating the lower inverter efficiency. On cloudy days with low irradiation this advantage disappears and the microinverter system shows lower final yield values compared to the two other systems.

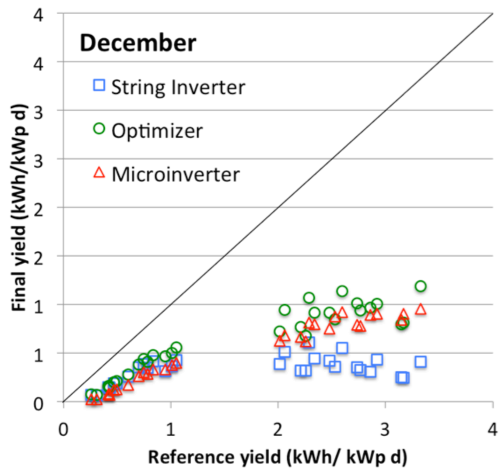

Fig. 11: Final yield vs. reference yield for the three inverter systems in December 2015

Figure 12 shows the average daily yield values per month of the three systems for one year of operation (4/6/2015 – 3/6/2016). The green and the red line indicate performance of the optimizer system and the microinverter system relative to the performance of the string inverter as a benchmark. During summer under homogeneous shading conditions the optimizer system shows similar values compared to the string inverter. With the beginning of partial shading in September the optimizer system shows higher average daily yield values. In December the yield of this system is 92 %

higher compared to the string inverter. For the whole year the optimizer system achieves a 8 % higher yield.

During summer the microinverter system shows a lower performance of 9 % - 10% compared to the string inverter. In October the advantage of the decentralized MPP-tracking under increasing heterogeneous shading compensates the lower inverter efficiency compared to the string inverter. In December the microinverter system achieves a 57 % higher yield than the benchmark system. For the whole year the microinverters have a slightly lower yield of -5 % compared to the string inverter.

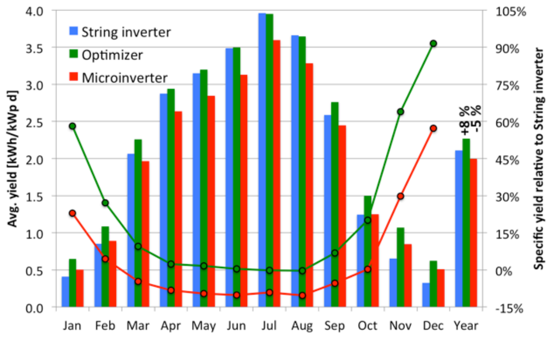

Fig. 12: Average daily yield per month of the three systems (4/6/15 – 3/6/16)

4 CONCLUSIONS

- Reduction in yield depends on the type of shading and the string design.
- Under heterogeneous shading conditions within strings decentralized inverter systems can achieve significantly higher yields compared to string inverters. On a month base + 92 % for the system with power optimizers and +57 % for the microinverter system were measured.
- Under homogeneous shading conditions and adjusted string design no increase in yield could be measured for decentralized inverter system. In this case the lower inverter efficiency of the microinverter system leads to lower yield values compared to the string inverter.

5 OUTLOOK/WORK IN PROGRESS

- Continuing measuring campaign to obtain long-term operational data
- Comparison of measured values with results obtained from simulation tools
- Comparison with historical data of the plant and evaluation of repowering

6 REFERENCES/PUBLICATIONS OF MAIN AUTHOR

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