Reactive Power Flows of Photovoltaic Inverters with a Power Factor Requirement of One

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ABSTRACT: The generated power of photovoltaic (PV) systems represents a growing part of the electrical energy supply in Germany. At the beginning of 2013, more than 32 GW have been installed [BUR-13]. This leads to new challenges to ensure the required grid stability. Due to the rapid extension of PV systems, primarily in low voltage grids, the state of the grid is increasingly unknown. This paper discusses reactive power flows due to PV inverter systems. The focus hereby is on the power factor (PF) requirement of one. Hence PV inverters should feed only active and no reactive power into the grid. Various observations in low voltage grids show a dispersion of the active and apparent power feed in and thus a reactive power flow. The direction and extend of these reactive power flows are analysed within this paper.

Keywords: Grid Integration, Photovoltaic, Reactive Current

1 INTRODUCTION

Most of the installed PV inverters in low voltage grids do have a power factor requirement of one. Hence, these inverters should feed in only pure active and no reactive power. Several observations in low voltage grids with a high PV penetration show a dispersion of the active and apparent power at feeders with a huge number of PV systems and thus a reactive power flow. The aim of this investigation is to analyse if these reactive power flows can be attributed to PV systems. The standards regarding reactive power of PV systems nowadays will be explained in the following. After that reactive power flows of the most installed types of PV inverters with a PF requirement of one will be shown.

NOWADAYS

All new built generation plants have to contribute to the static voltage stability to utilize the grid optimally. This is defined in the German low voltage guide line VDE-AR-N 4105 [VDE-4105]. The declaration day of application of this regulation is 2011-08-01. To achieve the regulations, PV inverters have to consume or supply reactive power by specified characteristic curves (e.g. $\cos\varphi(P)$ or $Q(V)$) respectively fixed shift factors. For example PV systems with an apparent power higher than 13.8 kVA have to follow a characteristic specified by the grid operator within the range $PF = 0.9_{leading} - PF = 0.9_{legging}$. PV systems smaller than 13.8 kVA and bigger 3.68 kVA have to follow a $PF = 0.95_{leading} - PF = 0.95_{legging}$ characteristic. A fixed shift factor is allocated to smaller PV systems. Besides the stabilisation of the voltage, reactive power flows cause additional losses in the grid. Of course these losses are not desirable but are accepted to achieve the voltage stability.

High feed in powers lead to high grid voltages. These high voltages can be counteracted by reactive power consumption. On the other hand a reactive power supply increases the grid voltage. Figure 1 and Figure 2 illustrate the voltage rise / drop along a low voltage line. The chosen apparent power leads to voltage rises / drops higher than the allowed 3 % [VDE-4105] of the nominal voltage which is a consequence of the allowed voltage variation of maximum 10 % [DIN-50160]. The chosen PF is 0.7. Due to this postulation the illustrated pointers do not represent real grids but make the relationships more obvious.

The grid voltage represents the slack voltage in the low voltage grid, V_{PV} respectively V_{Load} are the voltages at the end of a cable. Along this cable a voltage rise / drop (dV_{Cable}) occurs. This rise / drop is composed of a rise / drop over the line resistance and the line reactance. The capacitive line coverings are neglected. A negative apparent power represents a feed in; positive apparent power characterizes consumption.

In the upper part of Figure 1 an active and reactive power supply is displayed. Due to that the voltage at the connection point of the PV system is much higher than the slack voltage. The lower part illustrates an active power feed in and reactive power consumption. This leads to a reduced voltage rise over the cable. Figure 2 demonstrates the same relationships for the connection of a load.

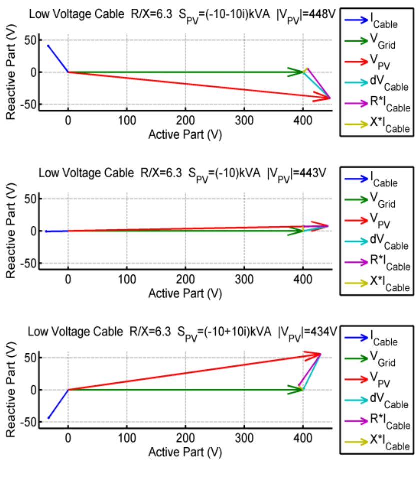

Figure 1: *Influence of the reactive power on the voltage in a low voltage grid with an R/X ratio of 6.3. A negative apparent power corresponds to a feed in.*

SOME YEARS AGO

In comparison to the specifications of [VDE-4105], the behaviour of older PV inverters for a nominated pure active power feed in (PF = 1) is not entirely clear. Most of the installed inverters do have this PF = 1 adjustment. This fits with the older low voltage grid guide line [VDEW-2005] where a PF between 0.9 capacitive and 0.8 inductive is required.

Despite the inverter specifications of a pure active power supply, a reactive power flow occurs. These reactive power flows will be analysed at different inverter structures in this work. The aim is to improve the knowledge of these power flows and to increase the security of the overall grid stability. The medium parts of Figure 1 and Figure 2 elucidate the length of the different pointers for a pure active power supply / consumption. The resulting voltage rise / drop lays in-between the rises / drops with an additional reactive power supply / consumption. A small angle between the grid voltage and PV / load voltage arises as a result of the line reactance.

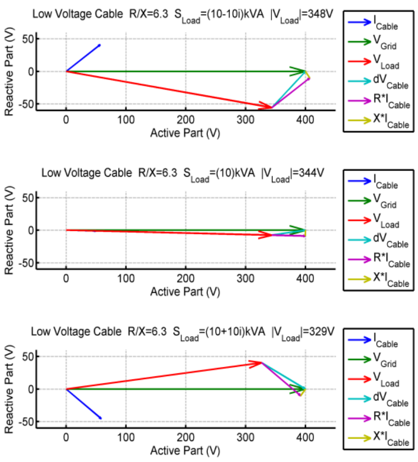

Figure 2: *Influence of the reactive power on the voltage in a low voltage grid with an R/X ratio of 6.3. A positive apparent power corresponds to a load.*

If PV systems cause a reactive power flow additional losses over the cable impedance ensue. Of course these losses are not desirable. On the other hand the voltage, especially at long feeders, can be positively influenced via reactive power control. At an unknown direction of the reactive power flow, respectively the reactive power flow of older inverters, the voltage can even be deteriorated. This investigation is done to understand the unintended reactive power flows of older PV inverters.

2 EXPERIMENTAL SETUP

In order to be independent of the current irradiation situation a PV generator simulator (Spitzenberger Spies – PVS 7000 [PVS-7000]) is used and fed with different irradiation and temperature profiles. The direct current (DC) output power corresponds to the input quantity of the examined inverter. The active and reactive power as well as the PF on the output side of the inverter are recorded with a power quality recorder (Fluke 1760 [FLU-1760]). Sinusoidal, trapezoidal and real global irradiation time series with different amplitudes and periods are considered.

The investigations are done for various different inverter structures and sizes that are typically used for roof top applications.

- Inverter Type I with a HERIC (Highly Efficient and Reliable Inverter Concept) topology.
- Inverter Type II with a H5 topology, including five switches.
- Inverter Type III including a high frequency (HF) transformer.
- Inverter Type IV including a low frequency (50 Hz - LF) transformer.
- Inverter Type V with no classical topology.

The irradiation time series and corresponding amplitudes for the sinusoidal and trapezoidal profiles are chosen to approximate real irradiation profiles. Various jump highs and period durations are examined. Figure 3 shows a trapezoidal irradiation profile with a start value of 1000 W/m², different period durations and jump highs.

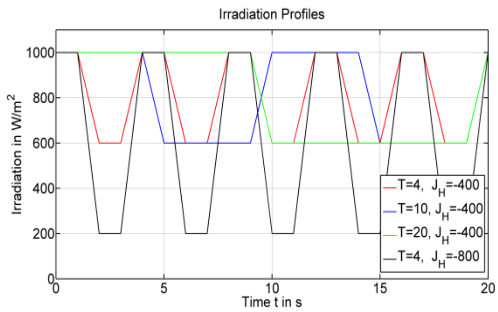

Figure 3: *Trapezoidal irradiation profile with a start value of 1000 W/m², different period durations and jump highs approximate real fluctuating irradiation profiles.*

The dependency of the reactive power flows on the amplitude and frequency of the irradiation and therefore the dependency on the utilisation rate (full load or part load operation of the PV system) will be analysed in the following part.

3 RESULTS

SINE TEST

The measured reactive power flow for various sinusoidal irradiation profiles includes almost entirely the steady component and fundamental oscillation of the irradiation profile. This can be based on a Fast Fourier Transformation (FFT) of the reactive power output as shown in Figure 4, Figure 5 and Figure 6. The results for one Type II Inverter, Type III Inverter and Type V Inverter for a period duration (T) of 10 s (first column in every figure) and 30 s (second column) and for the amplitudes (A) 100 W/m² (first row), 200 W/m² (second row) and 300 W/m² (third row) with an offset of constant 750 W/m² are displayed. The two other inverter topologies show the same behaviour. In general the irradiation can be calculated by formula (3-1).

$$\dot{G}(t) = 750\frac{W}{m^2} + A * \sin(\frac{2*\pi}{T} * t) \qquad (3\text{-}1)$$

The amplitude of the reactive power rises with increasing amplitudes of the irradiation. This relationship shows the fundamental oscillation of the reactive power flows. The first row represents irradiations between 650 and 850 W/m² whereas the third row reflects irradiations between 450 and 1050 W/m². Therefore the higher reactive power flows at higher amplitudes are either a result of a deeper part load operation or a higher full load operation. The direction (supply or consumption) of the reactive power flow cannot be seen in this FFT. However, there are reactive power flows despite a PF = 1 presetting and they depend on the amplitude of the irradiation.

A dependency of the reactive power flow on the irradiation frequency is not recognizable. There are no higher reactive power flows at shorter period durations. The absolute altitude of the steady component remains nearly constant. The fundamental oscillation depends on the amplitude of the irradiation but is independent on the irradiation frequency.

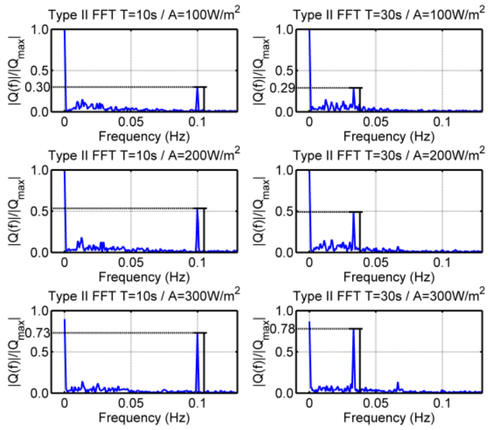

Figure 4: *Fast Fourier Transformation (FFT) of the reactive power for one Type II Inverter.*

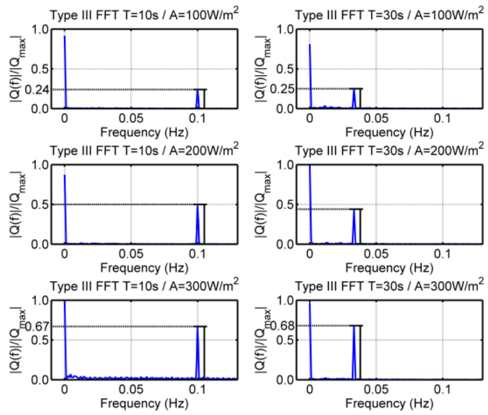

Figure 5: *Fast Fourier Transformation (FFT) of the reactive power for one Type III Inverter.*

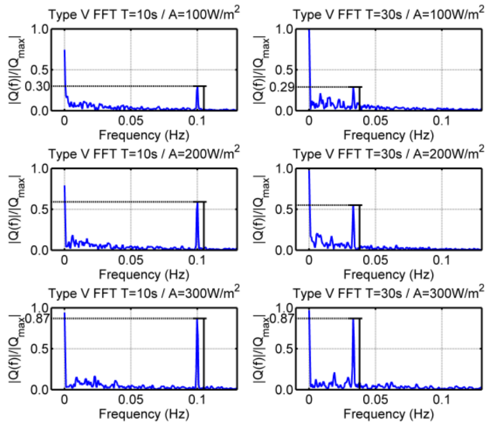

Figure 6: *Fast Fourier Transformation (FFT) of the reactive power for one Type V inverter.*

RECTANGLE TEST

For a more precise investigation the corresponding active and reactive power outputs for the rectangular irradiation profiles as shown in Figure 3 are examined. Period duration of 4 s, 10 s and 20 s and flanks heights of 400 and 800 W/m² are analysed.

The frequency dependency as well as the direction of the reactive load flow should be clarified. The inverter can behave as a reactive consumer (consumption of inductive power) and therefore having a voltage-reducing effect or as a reactive supplier (supply of inductive power) and having a voltage-boosting effect.

In the left column of Figure 7 the measured active power of one Type II Inverter is shown. During an irradiation of 1000 W/m² the nominal power ($P/P_r = 1$) is fed into the grid. In the last row at high irradiation gradients and short period durations the inverter is not able to reach its rated power. If the irradiation decreases, the active power declines as well.

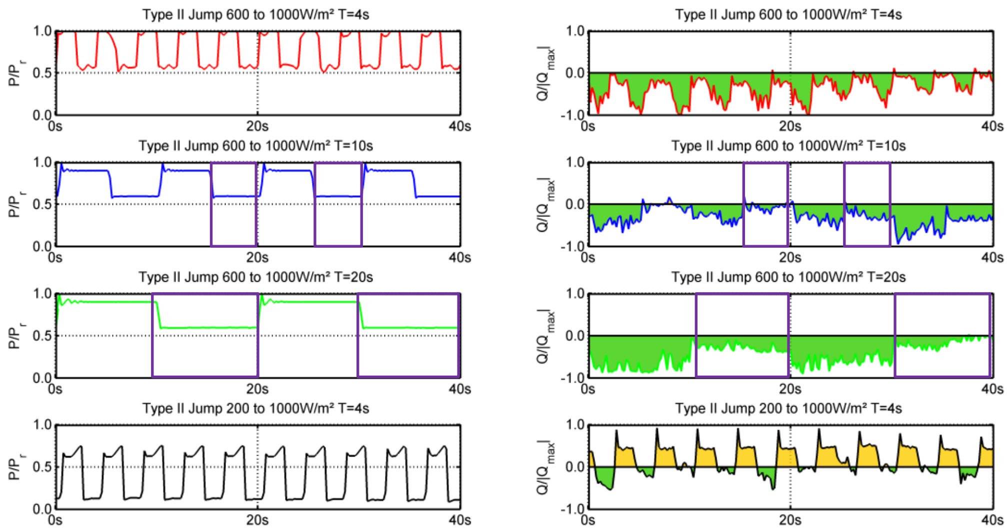

Figure 7: *Rectangle test of one Type II Inverter. In full load operation reactive power is consumed; in deep part load operation a reactive power feed in occurs. Hence this inverter has a positive influence on the voltage stability. However an unintended reactive power flow leads to additional losses in the grid.*

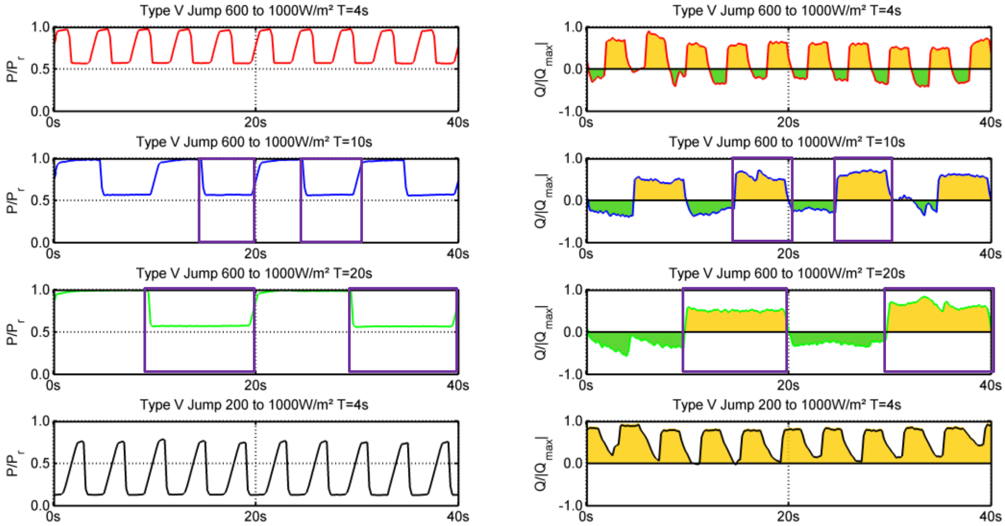

Figure 8: *Rectangle test of one Type V Inverter. In full load operation only a slight consume of reactive power is measured; in part load operation a higher reactive power is fed into the grid. Hence this inverter has a positive influence on the voltage stabilization especially in part load operation. However an unintended reactive power flow leads to additional losses in the grid.*

The right column shows the associated reactive power. In the first three rows almost no reactive power is fed into the grid. The highest reactive power consume is at full load operation. With a deeper part load operation, as shown in the fourth row, the inverter starts to feed in reactive power. Additionally a significant overshoot of the reactive power can be seen. There is a phase shift of 180° between active and reactive power.

In comparison to the results of the sine test the higher reactive power flows at higher irradiation amplitudes as seen in the FFT relate to the full load operation. This inverter contributes to the voltage stabilization. Reactive power consume at high active supply reduces the voltage whereas a reactive power supply in part load operation increases the voltage. Nevertheless, the unintended reactive power flows cause additional losses in the grid.

Figure 8 shows the results of the rectangle test for one Type V Inverter. There is slight reactive power consumption in full load operation and a higher supply in part load operation. In comparison to the results of the sine test the higher reactive power flows at higher amplitudes as seen in the FFT relate to the part load operation. Also this inverter contributes to the voltage stability. In the fourth row can be seen that the rated power at high irradiation gradients and short period durations is not reached. In contrast to the Type II Inverter there is no overshoot in the reactive power.

The inverter of Type I shows a similar behaviour as Type II. The highest reactive power consumption occurs at full load operation. No supply of reactive power arises. In part load operation there is no reactive power flow. Type III inverter has a high reactive power feed in in part load operation and almost no reactive power in full load operation. The Type IV inverter performs in part load operation as a capacity and in full load operation as inductivity.

To sum it up: All investigated inverters evoke reactive power flows. These reactive power flows cause additional losses in the grids but almost all of the inverters do have a positive influence on the voltage stabilisation.

REAL IRRADIATION PROFILES

To investigate the magnitude of the reactive power flows under real irradiation conditions, the PV generator simulator is fed with real irradiation profiles. The profiles were measured in 2012 in Lower Bavaria with a resolution of one second. Two different day courses are chosen; one representing a nearly perfect clear sky day the other a strong fluctuating day. The fluctuating day is the day with the highest irradiation gradients measured in this year. Therefore the survey is a worst case study.

Figure 9 and Figure 10 summarizes the results. In Figure 9 all active and reactive power flows and the corresponding absolute value of the power factor on a clear sky day for five examined inverter types are given. The active power follows the irradiation profile. The reactive power course looks similar for all investigated inverters except the Type I inverter. It shows a very smooth path without any fidgets. Nevertheless, the maximum reactive power values are very different among the individual inverters:

- The inverter of Type I behaves like a reactance. It consumes reactive power independent on the utilization degree. Due to that this inverter has a voltage-reducing effect. As a negative effect, it should be noted that the maximum reactive power consume of 800 VAr is the highest measured reactive power of all investigated inverters.

- A quite appreciated behaviour shows the inverter of Type II. This inverter feeds in reactive power in part load operation with a maximum of 70 VAr and consumes 100 VAr in full load operation. Thus the stabilization of the voltage is achieved. However, the path of the reactive power is very rough.

- The inverter of Type III feeds in reactive power in any degree of utilization. The reactive power has a maximum value of up to 300 VAr in deep part load operation and drops to almost zero at full load operation. Nevertheless even then a voltage boosting effect occurs. This is not desirable even if the voltage stabilization in part load operation is welcomed and no additional losses in full load operation emerge.

- Inverter Type IV displays an inductive behaviour over a wide utilisation range with a maximum of 200 VAr. A reactive power supply of up to 200 VAr arises only in deep part load operation. There is a voltage-reducing potential in almost any stage of operation available.

- The inverter of Type V performs like a capacitor in part load operation with a magnitude of up to 100 VAr. This inverter feeds in reactive power until the degree of utilization reaches around 2/3 of the nominal power. In full load operation this inverter also reduces the voltage and consumes reactive power. The voltage-reducing effect in full load operation is attenuated in comparison to Type I, II or IV. Also this inverter shows a strong roughness in the reactive power path. Therefore even in full load operation a reactive power feed in can occur.

None of the examined inverters feed in pure active power on a clear sky day. Nevertheless, all power factors except the power factor of Type I fulfil the pre-setting well.

Figure 10 shows the active and reactive power flows and the absolute value of the corresponding power factor for five examined inverter types on a day with fluctuating cloudiness. Noticeable is the active power course of the Type III inverter. At higher gradients of the irradiation the power drops to zero. A rectangle test returns a maximum jump depth smaller than 200 W/m² without disconnection. This problem should be solved in newer inverter structures. The Type I inverter shows again a quite smooth path compared with all other investigated inverter structures.

Again none one of the examined inverters feed in pure active power on a day with fluctuating cloudiness. Nevertheless, all power factors except the power factor of Type I and Type III fulfil the pre-setting well.

The magnitude of the reactive power flows on the day with a fluctuating cloudiness and a clear sky day are equal. A dependency on the irradiation frequency is again not visible. The reactive power flow depends only on the stage of utilization and thereby the amplitude of the irradiation.

For each examined inverter type the minimal inductive and capacitive PFs for both days are calculated. Furthermore the ratio of reactive power to active power in per cent is analysed. The fourth and seventh row of Table 1 and Table 2 imply the stage of operation when the minimal PF occurs. The performance of all inverters except the Type V inverter is improved on the clear sky day in comparison to the fluctuating day. The Type V inverter shows a nearly equal performance on the clear sky and on the fluctuating day. The minimal capacitive PF for all investigated inverters except inverter Type I is lower than the minimal inductive PF. If the reactive power feed in is higher than the active power feed in PFs lower than $1/\sqrt{2}$ (= 0.707) are the consequence.

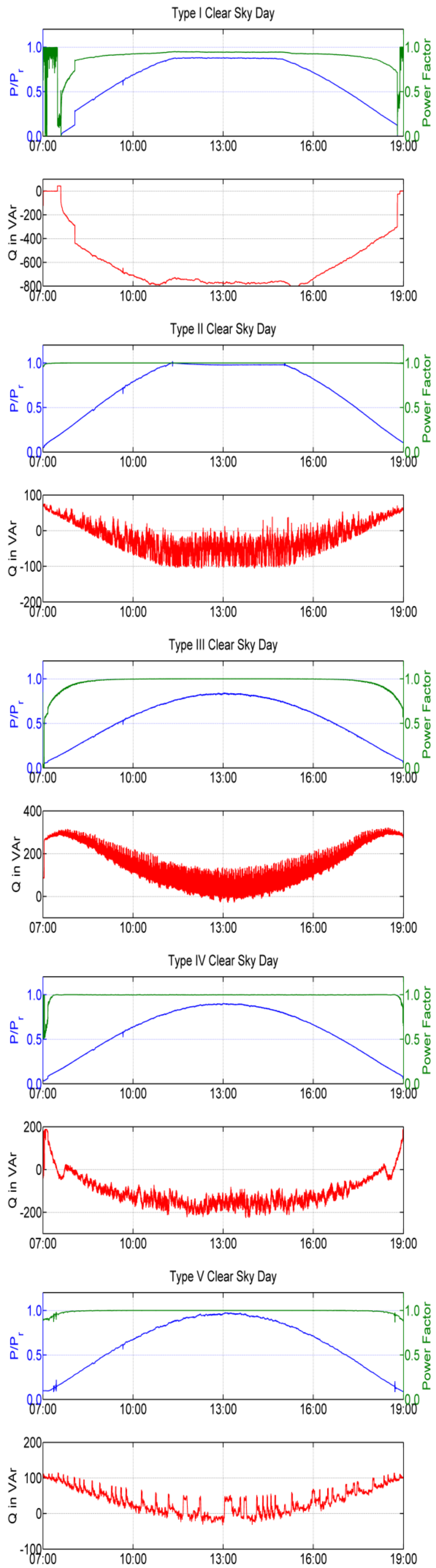

Figure 9: *Active and reactive power flows and power factor for five examined inverter types on a clear sky day.*

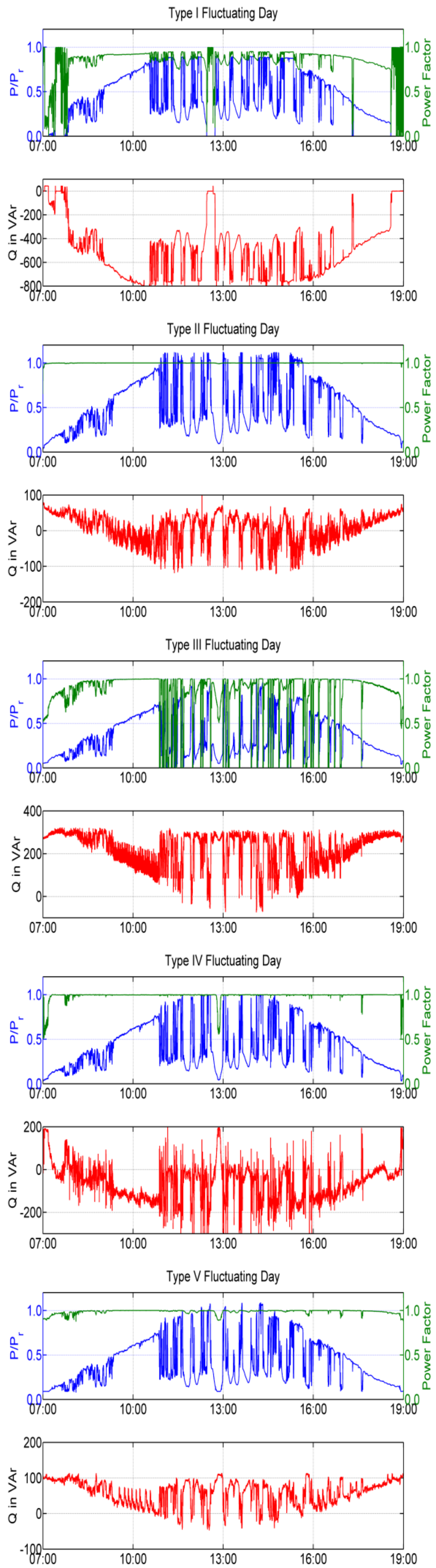

Figure 10: *Active and reactive power flows and power factor for five examined inverter types on a day with fluctuating cloudiness.*

In full load or near full load operation the active power is much higher than the reactive power. Thus the PF reaches high values. In comparison to that the part load operation shows a small active power feed in. Meanwhile the reactive load flow can be higher. Type II, III and V inverter only consume an amount less than 3 % of reactive power referred to the active power in full load operation. This leads to preferable PF higher than 0.999.

Nevertheless a higher PF in full load operation can lead to higher reactive power flows. The Type II inverter has a minimal inductive PF in full load operation of 0.9998. Thereby a reactive power consume of around 100 VAr emerges. The minimal capacitive PF is 0.9520 at an active power supply of 220 W. The resulting reactive load flow is around 70 VAr. Thus the reactive power flow in full load operation is higher than in part load operation despite the distinctly better power factor in full load operation. The Type I and II inverters do have the maximum reactive power flows in full load operation. Both types behave like a reactance. Type III and V inverters do have higher reactive power flows in part load operation and behave like a capacitor. The inverter Type IV reveals equal high maximal reactive power flows. Also this inverter behaves like a reactance in full load and a capacitor in part load operation.

4 SUMMARY AND CONCLUSION

A survey of various PV inverters with a fixed power factor (PF) requirement of one is carried out. The examined inverters are connected to a PV generator simulator and fed with different irradiation profiles. The output voltage and current of the inverters are measured with a power quality analyzer.

Synthetic irradiation profiles and real measured profiles are taken into account. Despite the PF = 1 requirement all investigated inverters supply or consume reactive power. The power factor pre-setting is fulfilled in full load operation. In part load operation partly high deviations of the PF = 1 adjustment appear.

A dependency of the reactive power on the amplitude of the irradiation can be obtained. Deeper part load operation, respectively lower irradiation values, can lead to higher reactive power load flows. This was shown for the Type III and V inverter. A dependency on the frequency of the irradiation-change is not visible.

There are large differences in the behavior of the inverters. One type shows a smooth path in the reactive power consumption. Others do have higher reactive power flows in full load operation than in part load operation. To sum it up, PV inverters with a fixed PF of one contribute to an uncontrolled reactive power flow in the grid.

This reactive power flows do have effects on the grid voltage and the losses in the cables. As illustrated, most of the analyzed inverters consume reactive power in full load operation. This corresponds to a voltage-reducing effect. Therefore the unintended reactive power flows do have a positive influence on the grid voltage stability. Nevertheless there are additional losses in the grid. That is the negative impact of uncontrolled reactive power flows. In further research work the influence of the unintended reactive power flows on the grid voltage and the losses in the cables will be examined.

Table 1: *Minimum capacitive and inductive PF and the corresponding reactive power referred to the active power for the five examined inverter types on a clear sky day. PL (Part Load) and FL (Full Load) imply the stage of operation.*

	$\cos(\varphi)_{cap\_min}$	$\frac{Q}{P}$ $at\cos(\varphi)_{cap\_min}$ in %		$\cos(\varphi)_{ind\_min}$	$\frac{Q}{P}$ $at\cos(\varphi)_{ind\_min}$ in %	
Type I - HERIC	1	0	--	0.5124	79.6	PL
Type II – H5	0.9815	19.5	PL	0.9998	2.0	FL
Type III – HF transformer	0.5595	148	PL	0.9999	1.4	FL
Type IV – LF transformer	0.5225	163	PL	0.9950	10.0	PL
Type V	0.8670	57.5	PL	0.9999	1.4	FL

Table 2: *Minimum capacitive and inductive PF and the corresponding reactive power referred to the active power for the five examined inverters on a day with fluctuating cloudiness. PL (Part Load) and FL (Full Load) imply the stage of operation.*

	$\cos(\varphi)_{cap\_min}$	$\frac{Q}{P}$ $at\cos(\varphi)_{cap\_min}$ in %		$\cos(\varphi)_{ind\_min}$	$\frac{Q}{P}$ $at\cos(\varphi)_{ind\_min}$ in %	
Type I - HERIC	1	0	--	0	--	--
Type II – H5	0.9520	32.2	PL	0.9998	2.0	FL
Type III – HF transformer	0	--	--	0.9997	2.5	FL
Type IV – LF transformer	0.4998	173	PL	0.9494	33.1	PL
Type V	0.8755	55.2	PL	0.9998	2.0	FL

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