Grid-Connected PV Power Plant Induced Power Quality Problems – Experimental Evidence

Pertti Pakonen, Antti Hilden, Teuvo Suntio, Pekka Verho
TAMPERE UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF ELECTRICAL ENGINEERING
Korkeakoulunkatu 3
Tampere, Finland
Tel.: +358 3 311 511
Fax: +358 3 3115 3015
E-Mail: pertti.pakonen@tut.fi
URL: http://www.tut.fi/

Keywords

«Flicker», «Harmonics», «Photovoltaic», «Power quality», «Renewable energy systems»

Abstract

This paper presents new findings on phenomena contributing to flicker and voltage variations caused by grid-connected photovoltaic (PV) inverters. The voltage variations caused by two different 6 kW single-phase grid-connected PV inverters were studied during climatic variations by varying their grid-coupling impedance. Two different methods for characterizing the PV-plant induced voltage variations were studied: the short-term flicker index (P_{st}) and the 10 minute very-short voltage variation value (VSV). The results clearly indicate that PV inverter power fluctuations induced by cloud shading and enhancement have a significant effect on the VSV value, but not on P_{st}. PV inverters have a clear effect on the P_{st} as well, but the main contributors are related to the inverter design rather than the power fluctuations caused by clouds. The main contributor in the elevated P_{st} values could be traced back to the poor design of the maximum power point tracking (MPPT) of the inverters. The MPPT caused subharmonic current variations at a frequency of approximately 8 Hz which is close to the most sensitive frequency of human eye. Another factor causing rapid voltage variations in low irradiance conditions was the current transients related to the inverter start-up and shut-down. Harmonic current distortion is also a potential PV inverter related power quality (PQ) issue. This study indicates that although the current total harmonic distortion (THD) may be very large at low power levels the total demand distortion (TDD) of the PV inverters is almost constant regardless of the output power and the harmonic current had only a very limited effect on the voltage quality even at the weakest network having a short-circuit current of I_{sc}=250 A. Thus, voltage variations caused by the PV inverters were the main PQ issue in the studied networks. The investigations also clearly show that a part of the power quality problems found in the PV plants are caused by the poor design of the PV inverters.

1. Introduction

During the past 15 years global installed PV capacity has increased approximately 45 % each year [1]. Residential rooftop PV generation has become a popular form of distributed generation (DG). This poses new challenges for distribution network operators (DNOs), because high PV penetrations may cause serious voltage quality problems [1-3]. Especially, in networks with low short-circuit current capacity it may be difficult to maintain the voltage characteristics defined in EN 50160 [4]. To ensure the compatibility between the PV installations and the power grid, the contribution of both the vendor of the PV installation and the DNO is needed. The PV plant and power grid characteristics should be taken into consideration already when a customer is planning a PV installation.

Due to the intermittent nature of the solar irradiance, PV plants cause voltage fluctuations in the power network. Single-phase PV inverters commonly used in single family houses are also likely to cause voltage unbalance. The magnitude of the voltage fluctuations and unbalance at the PV plant point of

connection depends on the network impedance and especially in weak rural networks the problems may become severe. Conventionally, voltage fluctuations have caused concerns mainly due to light luminosity changes which are characterized by short-term and long-term flicker indices P_{st} and P_{lt} defined in [5]. For public electricity networks EN 50160 [4] states that the long-term flicker index should be $P_{lt} \leq 1$ during each period of one week. To accomplish this, EMC standards such as IEC 61000-3-3[6] and IEC 61000-3-11[7] require that the flicker emissions of an individual power equipment at the supply terminals of the equipment under test (EUT) must not exceed $P_{lt} = 0.65$ and $P_{st} = 1$. Earlier, flicker has been reported as the most common reason for power quality complaints in many studies [8, 9]. Due to the introduction of compact fluorescent light (CFL) and light emitting diode (LED) lighting the sensitivity of lights to voltage fluctuations has generally decreased [10]. However, some non-dimmable LED lights have showed even larger sensitivity to voltage changes than incandescent lights [11] and halogen lighting is still widely used. Recent studies have indicated that voltage fluctuations may also cause additional stress and shorten the life of switch-mode power supplies (SMPSs), adjustable-speed drives (ASDs) and other electronic equipment having a full wave rectifier with smoothing capacitor at the mains input stage [12]. The main reason is the increased RMS ripple current, which causes temperature rise and accelerates the aging processes of the capacitor. Furthermore, voltage unbalance may cause additional stress to electronic equipment using three-phase rectifiers in the mains input stage due to the transition of the rectifier stage from three-phase operation to single phase operation [13]. Recently, there has been discussion on renewing the characterization of voltage fluctuations based on flicker indices and in addition to the flicker indices defined in [5] a novel method for characterizing the voltage fluctuations was proposed in [14].This method was studied also in this paper in characterizing the voltage variations caused by the PV plant in different irradiance conditions. Another widely studied power quality issue related to PV installations is the harmonic emissions of PV inverters [2, 3, 23]. Especially, at low output power levels the current THD of the PV inverters may be high – several tens of percent. This paper studies these two power quality issues of PV installations in different network and climatic conditions.

2. Measurement setup

The measurement setup used in this study is presented in Fig. 1. It consists of three 230 V single phase PV inverters connected in a wye configuration. A variable network coupling impedance was connected between the inverters and the LV network to enable adjustment of the short circuit current and R/X-ratio of the network connection.

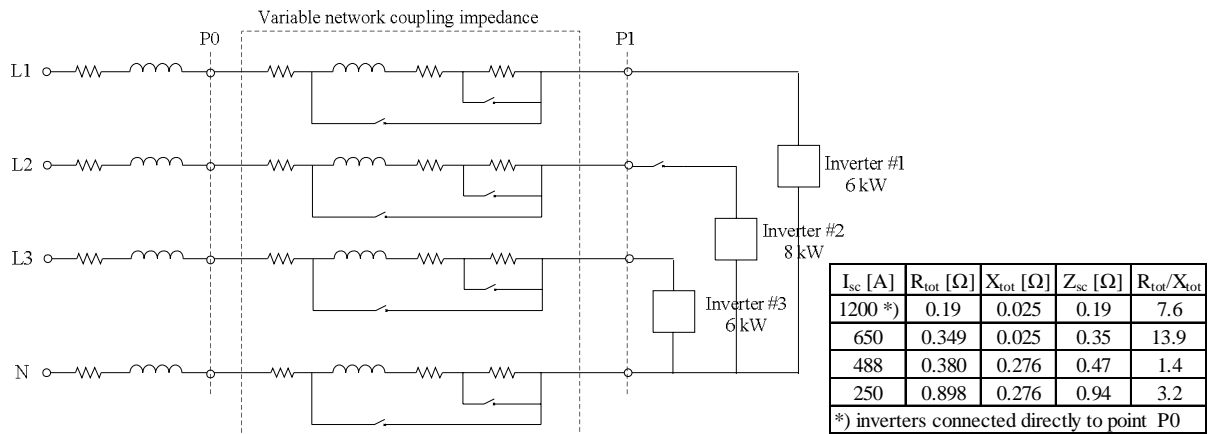| I_{sc} [A]	R_{tot} [Ω]	X_{tot} [Ω]	Z_{sc} [Ω]	R_{tot}/X_{tot}
1200 *)	0.19	0.025	0.19	7.6
650	0.349	0.025	0.35	13.9
488	0.380	0.276	0.47	1.4
250	0.898	0.276	0.94	3.2
*) inverters connected directly to point P0				

Fig. 1: Measurement setup and the network impedances.

The arrangement enabled operation of the inverters in four different network conditions with single-phase short-circuit currents (I_{sc}) of 1200 A, 650 A, 488 A and 250 A, respectively. The corresponding connection impedances and R/X-ratios of the network are presented in Fig. 1. The networks with 1200 A and 250 A short-circuit currents represent quite typical LV network R/X-ratios, whereas the 488 A network has a considerable inductive reactance component and its R/X-ratio represents the lower end of LV network R/X-ratios and approaches those found in typical MV network connections [15]. Single

phase short-circuit currents of $I_{sc} \approx 250$ A at the customer supply terminals are quite common, especially at rural networks. Short-circuit current $I_{sc} = 488$ A corresponds the reference network specified in EMC standard IEC 61000-3-3 [6] for voltage variation measurements of power equipment. Short-circuit currents of $I_{sc} = 650$ A and $I_{sc} = 1200$ A are common in city networks. During the measurements, inverter #2 was disconnected from the network and both inverters #1 and #3 were connected simultaneously to the network unless otherwise specified. The measurement results presented in this paper represent typical phenomena observed in the PV plant during several tens of days of measurements between June and August 2014 and 2015.

The PV power plant consists of 69 PV panels having peak power of approx. 13 kW. The PV panels are organized as three strings consisting of 17-23 panels in series. In this study, each string contained 17 series connected panels resulting a measured MPP power of 3230 W at 1000W/m^2 irradiation intensity. The PV system is equipped with versatile sensors for irradiation, temperature as well as a weather station. The data acquisition frequency is 10 Hz allowing recognition of the true dynamics of the phenomena taking place in the power plant. The PV power plant is described in detail in [16].

3. Rapid voltage changes and flicker

Rapid power variations caused by shading due to, for example, passing clouds are a typical phenomenon in PV systems [17]. Rapid and large power variations may cause flicker, additional stress to electrical equipment and malfunction of sensitive equipment in the network. Earlier studies have not found significant correlation between PV plant power fluctuation and flicker [18, 19]. Measurements and analysis presented in this paper support the conclusion that power fluctuations induced by moving clouds do not cause flicker to LV system. Fig. 2 shows the apparent powers and short-term flicker indices P_{st} of inverters #1 and #3 measured in the test setup with different short-circuit currents with both inverters in operation simultaneously. Apparent power is used as the power quantity, because both active and reactive power have an effect on the voltage variations. The P_{st} is highest in the morning and in the evening (a) when the inverter power is low, but decreases in the mid-day when the power variations are highest (b). Also the short-term flicker indices (P_{st}) presented in Fig. 3 indicate that power fluctuations during a partly cloudy day do not result in higher P_{st} values compared to a clear day even in a networks with a low short-circuit capacity (I_{sc}=250 A). In both partly cloudy and clear day $P_{st} \approx 0.8$ most of the daytime. The negligible effect of cloud induced power variations may be explained by the rate of change of power caused by cloud shading, which is relatively low from the flicker point of view. An extensive amount of irradiance data has been analyzed in [17] from the PV site used in this study. The average irradiance transition due to clouds lasted 16.3 s and the fastest change was 0.9 s. In this study a 50…80 % power change due to a passing cloud usually took several seconds, which means that the frequency of the voltage variations is at the least voltage sensitive edge of the flicker curve specified in [7]. Based on the measurements, reactive power variations of the inverters were small enough not to have any significant effect on the network voltage.

The high P_{st} values in the morning and evening and the increase of flicker with the increasing network impedance (Fig. 2, c) are explained by the observed rapid subharmonic current variations, which could be traced back to the poor design of the maximum power point tracker of inverter #3. With the network connection short-circuit current of $I_{sc} = 250$ A, the voltage quality would not fulfill EN 50160 due to excessive flicker. In inverter #1, these phenomena were considerably less pronounced. In fact, the flicker observed in case of inverter #1 is mostly due to the network neutral point displacement caused by inverter #3 current variations (d). The higher the neutral conductor impedance, the larger the neutral point displacement and the stronger the coupling of voltage variations and flicker between the phases. The subharmonic current variations are dealt with in more detail in section 4.

The voltage fluctuations were also studied by calculating the 10 min very-short variation (VSV) values using equations (1)…(3) presented in [14]. Examples of the VSV values on a sunny and a partly cloudy day in case of inverter #3 connected to the I_{sc}=250 A network are plotted as a function of time in Fig. 3 together with P_{st}, per unit voltage and apparent power fed by the PV inverter to the network. Two distinct differences can be found between the VSV and P_{st} plots. Firstly, the subharmonic current

variations cause a clear elevation of the P_{st} level in the morning and evening (e), but they are negligible in the VSV plot. Secondly, the relatively slow power varitions caused by passing clouds during the partly cloudy day do not have an effect on the P_{st} value, but have a distinct effect on the VSV value (f). During the sunny day the only relevant VSV peaks are related to the stepwise changes in the LV network voltage level caused by either abrupt load changes or transformer tap changing (g).
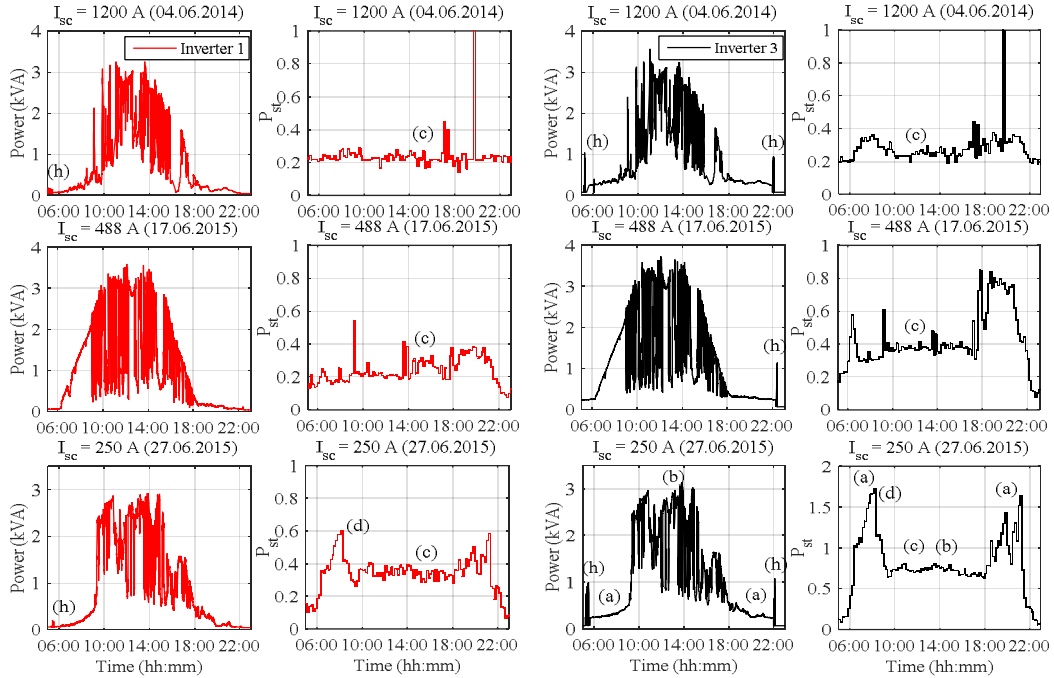

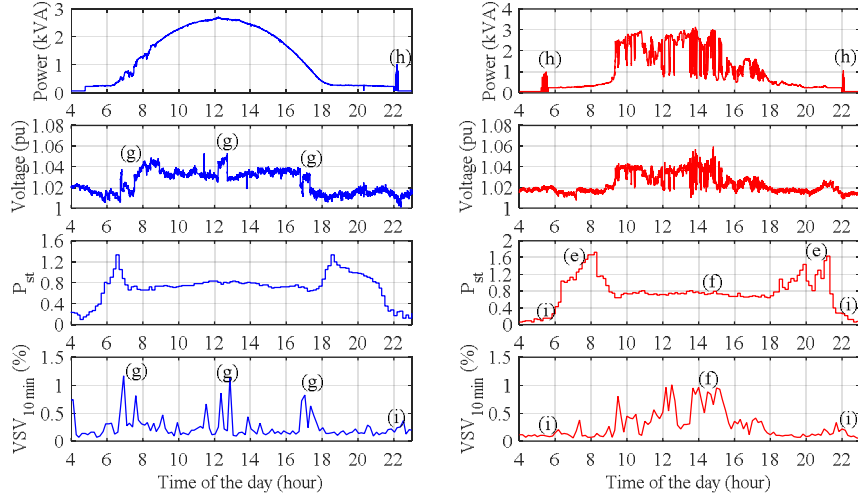Fig. 2: Apparent power variations and flicker index of inverters #1 and #3 in different networks.

Fig. 3: Apparent power, voltage, flicker index and very-short voltage variations (VSV) of inverter #3 on a sunny and partly cloudy day.

Poor design of an inverter may also lead to current transients and rapid voltage changes in the morning and in the evening when the inverter powers up or shuts down. These transients are clearly visible as apparent power peaks in the morning and evening in Figs. 2 and 3 (h), especially, in case of inverter #3. The short transients at the start-up and shut-down of the inverter do not have any significant effect on either P_{st} or VSV values (i), but from the viewpoint of stress and disturbance to electronic equipment they are most relevant. The transients are dealt with in more detail in section 5. All these three types of voltage variations are detrimental from the network voltage quality point of view. Therefore, the standardization related to both PV inverters and network voltage quality should be developed in order to provide more incentive to limit the voltage variations caused by PV systems.

4. Subharmonic current variations

Analysis of the inverter DC and AC voltages and currents measured in the test setup revealed that the MPP-trackers of the inverters cause rapid subharmonic current variations, which have a significant contribution to flicker. As illustrated in Fig. 4 in case of inverter #3, the amplitude of these current variations were clearly higher than in case of inverter #1, with $I_{sc}=250$ A in the order of 1.5…2 A, which is approx. 15…25 % of the highest current changes caused by shading (j). However, the rate of change of current and the repetition frequency is higher, which makes the phenomenon more likely to cause flicker. An example of the subharmonic oscillations observed in case of inverter #3 is presented in Fig. 5. In low insolation conditions this subharmonic oscillation was constant leading to elevated P_{st} levels in the morning and evening. In higher insolation levels the subharmonic oscillation occurred only at the instants of the string DC voltage change (once every 1-2 seconds) and was damped quickly, but it still caused a clear elevation of the P_{st} level. The impact of the oscillations on the flicker index presented earlier in Fig. 2 and 3 was enhanced by the fact that the frequency of the oscillations was approximately 8 Hz (Fig. 5), which is very close to the frequency at which human eye is most sensitive to light luminosity changes [7]. The network impedance had an effect on the amplitude of the voltage variations caused by the subharmonic oscillations, but not on their frequency. In case of the network with 250 A short-circuit current the voltage variation was in the order of one volt (Fig. 5).
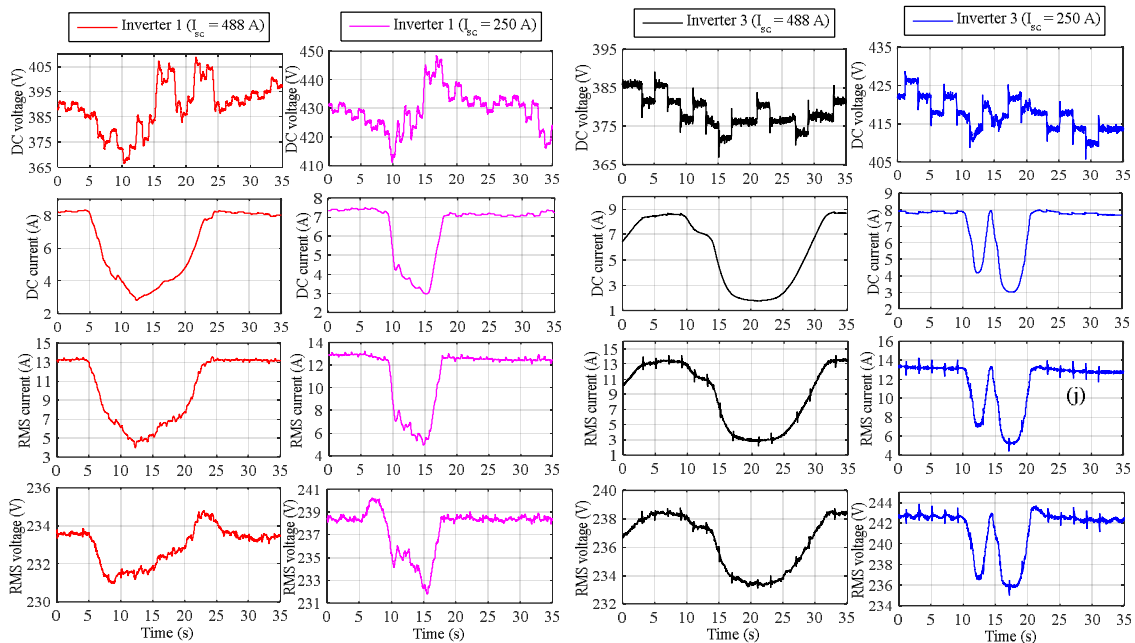

Fig. 4: Current and voltage variations related to the MPP tracker of inverters #1 and #3.
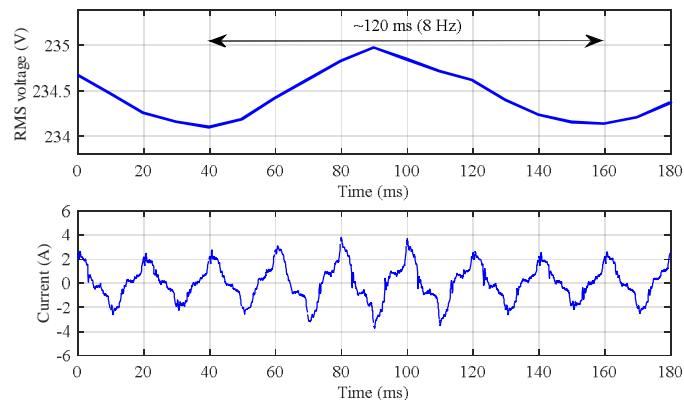

Fig. 5: Subharmonic current variation at a low irradiance level in terminals of inverter #3 (I_{sc}=250 A).

5. Transient currents at inverter start-up and shut-down

Current transients or bursts associated with the inverter start-up in the morning and shut-down in the evening were observed in both inverters. The current transients have an adverse effect on the voltage quality and may cause additional stress to other electrical equipment connected to the network. The waveform and amplitude of the transients depends on the inverter design as indicated in Fig. 6, but it was present in both of the inverters despite the different manufactures. In case of inverter #3 the current transients are high with a peak value of up to 20 A (Fig. 6, k), in case of inverter #1 the peak current is lower, approximately 3-4 A and it has a considerable amount of fundamental frequency and lower order harmonics (l). The transients could be repetitive for several minutes and they were present in all studied network configurations. The phenomenon is linked to the abrupt changes in the DC link voltage as illustrated in Fig. 7. In case of inverter #3, the current transients at the inverter start-up and shut-down are linked to the abrupt changes of DC voltage between the 300-340 V level when the inverter is connected to the network (voltage minimums) and the 400-480 V level when the inverter is disconnected from the network (m). In case of inverter #1, the 3-4 A current transients at the inverter start-up are linked to DC voltage changes between approx. 330 V level when the inverter is connected to the network and the 400-420 V level when the inverter is disconnected from the network (n).
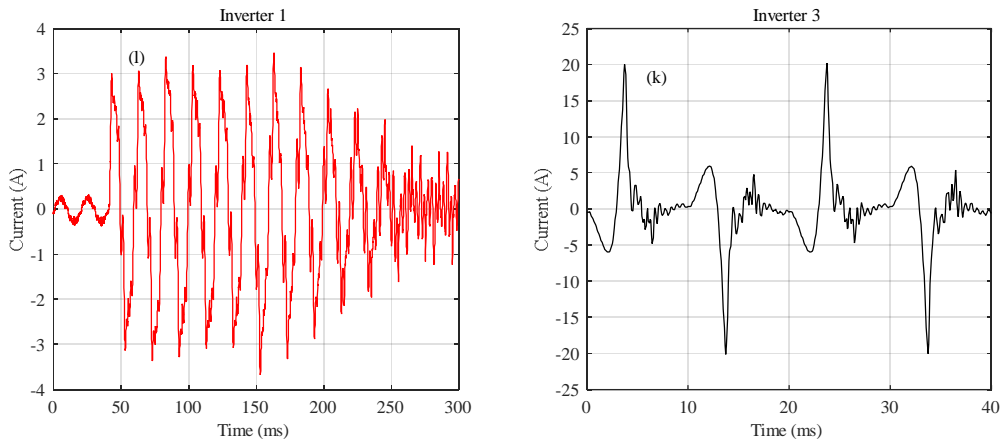

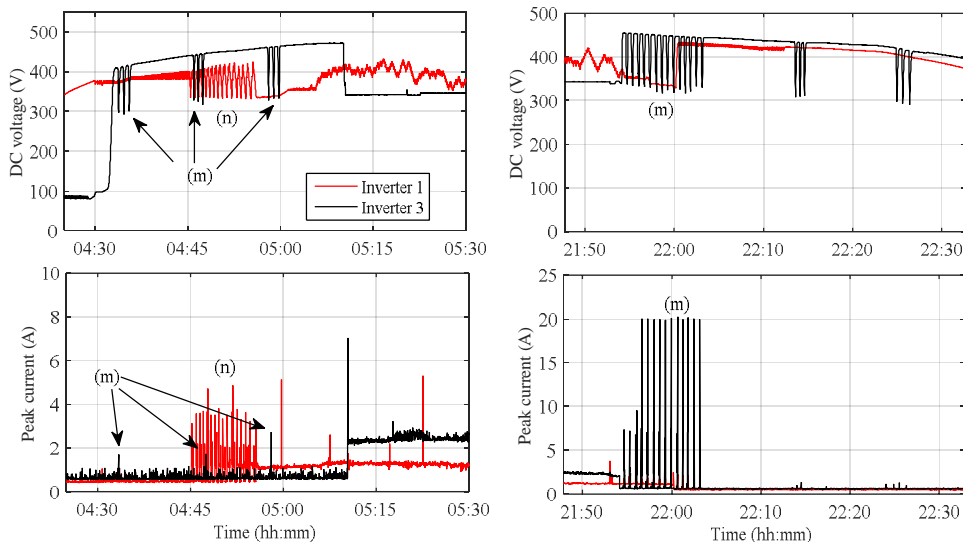Fig. 6: Current transients in the morning and in the evening ($I_{sc} = 488A$).

Fig. 7: DC voltages and current transients in the morning and in the evening.

6. Voltage level and slow voltage variations

Although the cloud induced power changes did not have a significant effect on flicker they cause rapid voltage changes, which may disturb voltage sensitive equipment or voltage controlled motor operation and stress electronic equipment. Fig. 8 illustrates the correlation between the irradiance and the

inverter DC and AC powers and voltage at the network supply terminals. The most rapid power change in the Figures is approximately 1.8 kW in 2 seconds. The AC output power of the inverter follows the insolation intensity almost instantaneously. Especially, in conjunction with cloud enhancement the rapid voltage changes can be large as illustrated in Fig. 8. In the left column of Fig. 8 (o) the cloud enhancement is manifested by the high intensity levels exceeding 1000 W/m^2. In the right column the cloud enhancement is much less pronounced, but the voltage variations are still large due to the low short-circuit capacity of the network (p).

In the measurement setup used in Fig. 8, doubling the PV string MPP power to correspond the nominal power of the inverter resulted in repetitive violation of the U_n+10 % limit in the network with I_{sc}=250 A. With typical string dimensioning used in the commercial residential PV systems the voltage variations may violate the $U_n \pm 10$ % limits in low load situations and cause the inverter to abruptly disconnect from the network or limit the power especially in weak rural networks. For rapid voltage changes there are currently no limits, only indicative values presented in EN 50160 [4]. VDE-AR-N 4105 specifies limits for rapid voltage changes and the frequency of their occurrence at the point of common coupling (PCC) for power generation systems connected to the LV distribution system [20]. In the network with I_{sc} = 250 A the VDE-AR-N 4105 limit was violated already with one PV string with MPP power of 3230 W. In practice, the extent of the problem depends on the amount and type of loads at the connection point of the inverter and the problem may also be mitigated to some extent utilizing the reactive power control of the inverter.
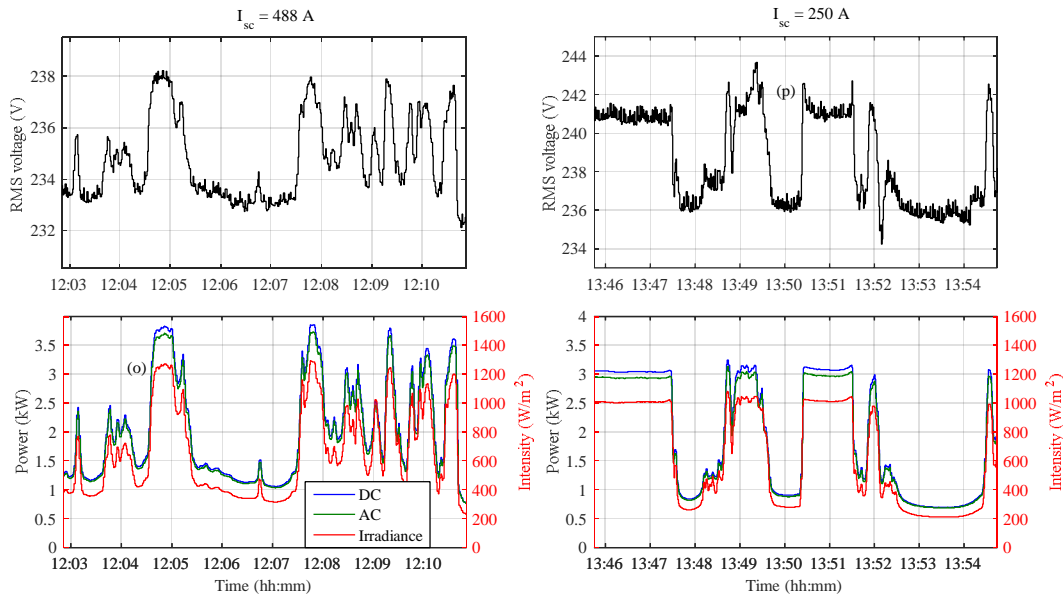

Fig. 8: Rapid voltage changes associated with power variations caused by passing clouds in networks with single-phase short-circuit current of I_{sc}=488 A and I_{sc}=250 A.

7. Harmonic current distortion

Harmonic currents produced by the inverter are known to depend, among others, on the instantaneous power produced by the inverter and the amount of voltage harmonics present in the grid [21]. Fig. 9 presents the total harmonic distortion (THD) and total demand distortion (TDD) of the inverter output current together with the apparent power and RMS phase voltage and the total harmonic distortion of phase voltage at the connection point between the inverter and the variable network coupling impedance. In case of both inverters the maximum demand load current used in the TDD calculation was 14 A (corresponding to the maximum output power of one PV string connected to the inverter). THD was high in the low insolation conditions, especially, in case of inverter #1 (q). However, the TDD remained fairly constant throughout the day in case of both inverters (r), which means that the high THD in the morning and evening is not necessarily a problem. In case of inverter #1 the TDD is approximately 1.3 % and in case of inverter #3 it is almost 4 %.

Although there is a clear difference between the TDD levels of the inverters, the impact of both inverters on the total harmonic distortion (THD) of the network voltage was negligible even at the network with the lowest short-circuit current I_{sc}=250 A (s). The current transients in the evening (and morning) dealt with in the previous chapter are visible at the apparent power as well as in voltage and current THD and TDD (t). Based on the measurement results presented in this chapter and the previous one it seems that voltage variations are the primary problem related to the PV plants and at least with low PV penetration the harmonic currents are not likely to cause problems.

The behavior of the inverter #1 and #3 current THD as a function of inverter fundamental active power during two whole days is illustrated in Fig. 10. Measurement data is presented in the first row (u) and moving average in the second row (v). Similar analysis was made for several days with very similar results. During these measurements only one inverter was operating at a time. Inverter #3 THD is generally higher except during the very low power levels, where inverter #1 THD is higher (u). In case of inverter #3 also the network R/X-ratio seems to have an effect on the THD level – with high R/X the THD is smaller (v). The observation is in line with [22] as higher network inductance seems to result in higher current distortion. In [22] it is suggested that higher inductance decreases the resonance frequency of the system and as a result increases the current distortion.
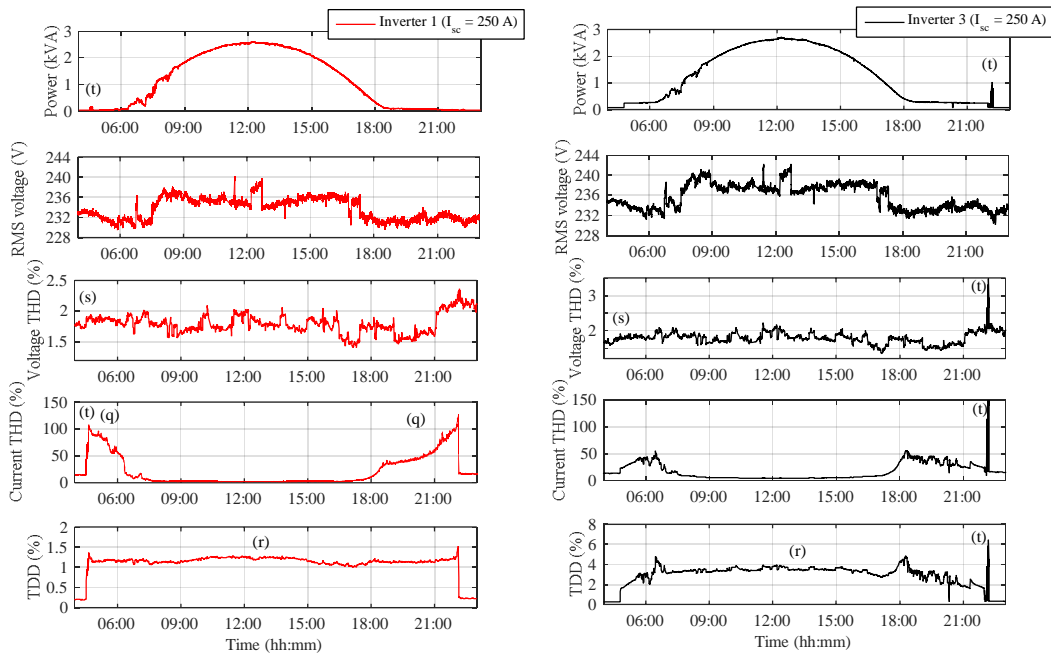

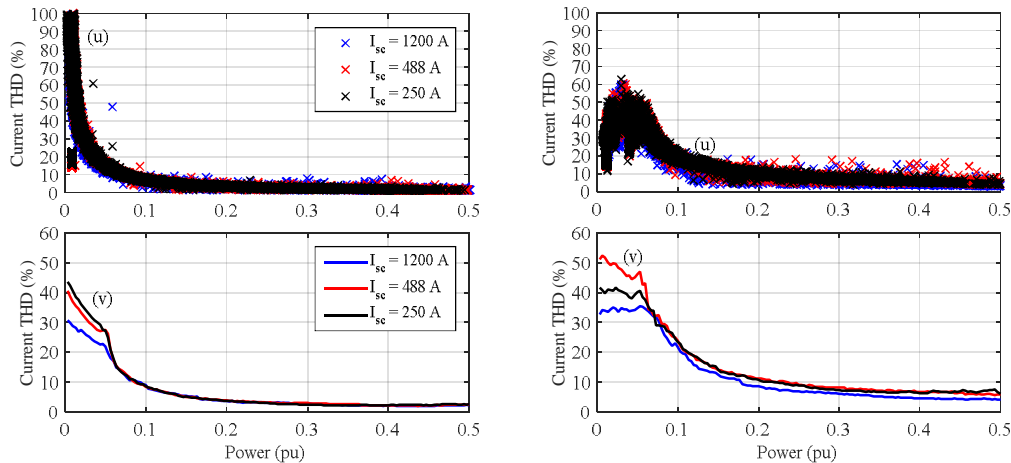Fig. 9: Apparent power, RMS voltage, voltage THD, current THD and TDD of the inverters.

Fig. 10: Current THD as a function of inverter fundamental active power in different network conditions.

8. Conclusions

Experimental results on the power quality impacts of single-phase grid-connected PV systems were presented in this paper. The main emphasis was on the voltage variations caused by the PV systems in different climatic conditions in different networks. Two different methods for characterizing the voltage variations caused by PV inverters were studied: the conventional short-term flicker index P_{st} defined in [4, 5] and the 10 minute very-short voltage variation value (VSV) defined in [14]. The results clearly indicate that PV inverter power fluctuations induced by cloud shading have a significant effect on the VSV value, but not on the short-term flicker index P_{st}. However, the power fluctuations induced by cloud shading have a strong impact on the network voltage level, especially in weak rural networks. Based on the results, in weak networks such as the studied network with $I_{sc}=250$ A the voltage variations caused by commercial residential PV systems may violate the $U_n\pm10$ % limits and cause the inverter to abruptly disconnect from the network or limit the output power.

The results indicate that PV plants increase the network P_{st} values, but the increase is mainly due to the poor design of the MPP-tracker of the inverters. The MPPT of inverter #3 caused subharmonic current variations at a frequency of approximately 8 Hz which is very close to the most sensitive frequency of human eye. The current transients associated with the inverter start-up and shut-down in low irradiation conditions also cause unnecessary voltage variations. Depending on the inverter design, the current transient peak values varied from a few amps to 20 A. The power variations induced by shading and cloud enhancement and the problems related to the PV inverter designs cause rapid voltage variations, which may stress the equipment connected to the grid and seriously degrade the voltage quality. Both the inverter and network voltage quality standardization should be developed to provide more incentive for limiting the rapid voltage variations caused by PV systems.

In addition to the voltage variations, the distortion of inverter output current was studied in different network and irradiance conditions. The total harmonic distortion (THD) of the inverter current relative to the fundamental frequency component was high in the low insolation conditions, especially, in case of inverter #1. However, the TDD and the absolute value of the distortion current remained at a moderate and constant level throughout the day regardless of the output power of the inverter in case of both of the inverters. As a result, the effect of the distortion current on the network voltage was very small even at the weakest network having a short-circuit current of $I_{sc}=250$ A. Thus, the main PQ issue in the studied networks was the voltage variations caused by the PV inverters.

The results indicate that the proliferation of grid-connected PV systems is likely to increase the need for voltage quality monitoring and management in public LV networks. Serious voltage quality problems may occur even due to small residential PV installations, if the local power network characteristics are not taken into account in planning and installing a new PV system. Therefore, it is important that both the vendor of the PV system and the DNO are aware of the potential problems related to PV installations and co-operate in order to ensure the compatibility of the installation with the grid. Correcting the problems afterwards is usually both difficult and expensive. The embedded measurement, data processing and control capabilities available in the PV inverters open up new possibilities also in monitoring and mitigating voltage quality problems in the network, but the potential is in any case limited.

References

[1]   M.S. ElNozahy and M.M.A. Salama, 'Technical impacts of grid connected photovoltaic systems on electrical network - A review', *J. Renew. Sustain. Energy*, vol. 5, no.3, pp. 2702:1-11, May 2013.

[2]   J.H.R. Enslin, and P.J.M. Heskes, 'Harmonic interaction between a large number of distributed power inverters and the distribution network,' *IEEE Trans. Power Electron.*, vol. 19, no. 6, pp. 1586-1593, Nov. 2004.

[3]   K. Fekete, Z. Klaic, and L. Majdandzic, 'Expansion of the residential photovoltaic systems and its harmonic impact on the distribution grid', *Renewable Energy*, vol.43, no. 7, pp. 140-148, July 2012.

[4]   EN 50160, 2010. Voltage characteristics of electricity supplied by public electricity networks, CENELEC. 63 pp.

[5]   IEC 61000-4-15. 2010. Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques - Flickermeter - Functional and design specifications. Ed. 2.0. International Electrotechnical Commission. 83 p.

[6]   IEC 61000-3-3. 2013. Electromagnetic compatibility (EMC) - Part 3-3: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems, for equipment with rated current ≤ 16 A per phase and not subject to conditional connection. Ed. 3.0. International Electrotechnical Commission. 69 p.

[7]   IEC 61000-3-11. 2000. Electromagnetic compatibility (EMC) - Part 3-11: Limits - Limitation of voltage changes, voltage fluctuations and flicker in public low-voltage supply systems - Equipment with rated current ≤ 75 A and subject to conditional connection. Ed. 1.0. International Electrotechnical Commission. 31 p.

[8]   S. Cobben, 'Power Quality Implications at the Point of Connection', PhD thesis, Technische Universiteit Eindhoven, 2007. 230 p.

[9]   M. Pikkarainen, P. Nevalainen, P. Pakonen, P. Verho, 'Practical Case Study: Measurement of Power Quality Problems Caused by Common New Loads', The 9th Nordic Electricity Distribution and Asset Management Conference NORDAC 2010.

[10] R. Cai, J. Cobben, J. Myrzik, J. Blom, and W. Kling, 'Flicker responses of different lamp types', *IET Generation, Transmiss. Distrib.*, vol. 3, no. 9, pp. 816–824, Sep. 2009.

[11] H. Sharma, F. Sharp, M. McGranaghan, 'Flicker/Voltage Fluctuation Response of Modern Lamps Including Those with Dimmable Capability and Other Low Voltage Sensitive Equipment', 22nd International Conference on Electricity Distribution, CIRED 2013.

[12] K. Zhao, P. Ciufo, S. Perera, 'Rectifier Capacitor Filter Stress Analysis When Subject to Regular Voltage Variations', *IEEE Trans. Power Electron.,* vol. 28, no. 7, pp. 3627-3635, July 2013.

[13] K. Lee, T.M. Jahns, W.E. Berkopec, 'DC-Bus Electrolytic Capacitor Stress in Adjustable-Speed Drives Under Input Voltage Unbalance and Sag Conditions', *IEEE Trans. Ind. Appl.,* vol. 43, no. 2, pp. 495-504, March/April 2007.

[14] M.H.J. Bollen, I.Y.H. Gu, 'Characterization of Voltage Variations in the Very-Short Time-Scale', *IEEE Trans. Power Del.,* vol. 20, no.2, pp. 1198-1199, April 2005.

[15] A. Engler, 'Applicability of droops in low voltage grids', *DER Journal*, no. 1, January 2005. pp.1-5.

[16] D. Torres Lobera, et al., 'Operation of TUT solar PV power station research plant under partial shading caused by snow and buildings', *Int. J. Photoenergy*, vol. 2103, pp. 1-13, 2013.

[17] K. Lappalainen, S. Valkealahti, 'Recognition and modelling of irradiance transitions caused by moving clouds', *Solar Energy* 112 (2015), pp. 55-67.

[18] S. Favuzza, F. Spertino, G. Graditi, G. Vitale, 'Comparison of Power Quality Impact of Different Photovoltaic Inverters: the viewpoint of the grid', IEEE International Conference on Industrial Technology (ICIT), 2004.

[19] P. González, E. Romero, V. M. Miñambres, M. A. Guerrero, E. Gonzalez, 'Grid-Connected PV Plants. Power Quality and Technical Requirements', Electric Power Quality and Supply Reliability Conference (PQ), 2014.

[20] VDE-AR-N 4105:2011-08. Power generation systems connected to the low voltage distribution network. Forum Netztechnik/Netzbetrieb im VDE. 78 p.

[21] G. Chicco, J. Schlabbach, and F. Spertino, 'Experimental assessment of the waveform distortion in grid-connected photovoltaic installations', *Solar Energy*, vol. 83, no. 7, pp. 1026-1039, Jul. 2009.

[22] J. Sun, 'Impedance-Based Stability Criterion for Grid-Connected Inverters', *IEEE Trans. Power Electron.*, vol. 26, no. 11, pp. 3075-3078, Nov. 2011.

[23] A. Chidurala, T.K. Saha, N. Mithulananthan, 'Harmonic Impact of high penetration photovoltaic system on unbalanced distribution networks – learning from an urban photovoltaic network', *IET Renew. Power Gener.*, vol. 10, iss. 4, pp. 485-494, 2016.