ANALYSING THE VOLTAGE STABILITY OF PHOTOVOLTAIC INVERTERS REACTIVE POWER CONTROL IN THE LABORATORY INCLUDING THE DISTRIBUTION GRID TRANSFORMER

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ABSTRACT:
Photovoltaic (PV) inverters increase the line voltage in Distribution Grids (DG) by active power feed in. Today, modern PV inverters are also able to feed in reactive power to mitigate the above voltage rise. The favoured, cost effective implementation is the control of reactive power feed in according to the instantaneous measured line voltage. The stability of this decentralised Q(U) PV inverter closed-loop control is mandatory and analysed in this work. The DG operator must guarantee the voltage limits given in the regulatory framework. This is challenging due to fast changing solar irradiance, load flows and the interaction of an overlying automatic voltage control-loop of a connected sub-station. The performed tests in the AIT SmartEST laboratory resulted in very stable operation even at small Time Constants (TC) below 5 seconds of the Q(U) control parameter. As one test scenario, an abrupt rise of solar irradiance immediately followed by load drop is realized by use of the PV and load emulators. The PV inverter reduces the resulting voltage rise by increasing its reactive power, depending on the Q(U) control time constant.
It was found that even at smaller Q(U) time constants than the typical applied values of 5 or 10 seconds no sign of instability arises. It is recommended to the DG operator to apply TC of 1 or 2 seconds of Q(U) control to minimise the duration of overvoltage condition during the transient voltage adjustment. Applying irradiance conditions of a typical cloudy day in the lab test yields 45% of the time the line voltage was above a given grid voltage limit, while applying Q(U) at TC of 1 second there was no occurrence of overvoltage. In detail at Q(U) TC setting of 20 seconds the overvoltage arises 3.4% of the total period and only 0.3% at TC 5 seconds. Only stable operation conditions were found including the automatic voltage control of the transformer sub-station at a typical setting of 10 seconds delay time of that sub-station control setting. Summarized, in combination with that delay time setting the smaller Q(U) time constant of the PV inverters below 5 seconds are beneficial due to the minimised overvoltage time.

Keywords: PV inverter, grid integration, voltage regulation, qualification and testing, cost reduction

1 MOTIVATION AND MARKET NEEDS

One of the main duties of the DG in the coming years is to deliver power and stay within the permitted grid voltage levels, even during periods of high Photovoltaic (PV) power feed into the grid. Further, costly hardware investments have to be evaluated economically and technically regarding the ability to stabilize the voltage according to the grid code [1].

An effective and low-cost approach is the control of the reactive power Q(V) and the active power P(V) of the PV inverter, by means of the actual grid voltage measured by the individual PV inverter [2,3]. Thus, no additional hardware investment in Information and Communication Technology (ICT) on the grid level is needed. The PV inverter settings of the static characteristics of the Q(V) and P(V) have to be in accordance with the grid operating code. Additionally, the time constants (dead and delay time) of these Q(V) and P(V) control activities have to be specified to guarantee a stable grid operation.

Today, this economically very attractive Q(V) method is not widely used in practice. To convince the DG operator, more effort of sophisticated tests have to be performed, including feedback loops of the tap changer controller of the transformers close to the stability boundary.

A report about such extreme laboratory tests are given in this paper, like results and analyses of stability measurements in the laboratory of PV inverters, powered by DC sources, emulating changing weather conditions, especially abrupt transient trigger by changing solar irradiance. Other transient inputs have been generated by different load, emulating Electric Vehicles (EV) charging stations.

The first published results of this test series here [6], will be extended here and tested including the use of the substation [4]. The transformers medium voltage On-Load-Tap-Changers (OLTC) in the lab will complete the total analysed control loop with the PV inverter in the main focus. It will be elaborated in the paper, if different appropriate settings of the parameters are needed for each category of distribution grids and type of the static Q(V) und P(V) characteristics. A set of stable parameters are given of the times constants of the controllers for each grid category including the demand of highest load transients occurring at EV charging. Finally, a suggestion is made of how these laboratory-based parameter findings should be introduced into a general standardization process.

2 DESIGN OF THE LAB TEST CASES

A commercial PV inverter is the Device-under-Test (DUT) of the experimental set-up in particular his implemented control regime of the line voltage based Q(U) method is tested as shown in Fig. 1 and 2. The direct current input of the PV inverter was feed by either as a change of active power or according the calculation of the current voltage characteristics of the PV generator according to the measured solar irradiance on a cloud day in the Zurich area. The goal was to measure instability occurring as oscillations of the line voltage.

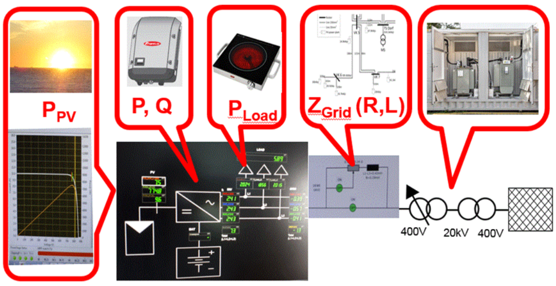

Figure 1: Engaged devices of the SmartEST labs to realise the stability test of the Q(V) feature of the PV inverter as the Hardware-under-Test (Hut).

Figure 2: Commercial smart secondary substation with OLTC as part of the SmartEST lab equipment embedded in the experiments.

3 CONFIGURATION OF TEST SETUP

Different static Q(U) characteristics and values of the TC of the inverters Q(U) setting was tested. Here the results are reported with the static Q(U) settings with a slope of 3% voltage rise resulting in the linear increase of reactive power from zero to the maximum, with a dead band of again 3% in between the positive and negative branches. [7]. The adjusted Q(U) time constants at the DUT is defined as first order filter in which the reactive power set point is reached after 1τ (63 %) of a voltage step. The lab experiment settings are adapted to the voltage drop along the real impedance in the DG of the village Dettighofen, from a farmer's house with a 100kW PV installation, located on the village rand, to the transformer in the centre of that typical village [2].

Thus, the voltage drop on the lab-impedance at the maximum active power of the DUT, which was smaller than 100KW, was comparable with the scaled slope of the static DUT Q(U) characteristics. The tests are performed with different TC settings between 1 to 20 seconds and with and without the connected sub-station transformer equipped with OLTC control.

The DEWE hardware and software solution are used to acquire the electrical measurements of the three-phase power and voltage and first analyses are found by the generated plots of the DEWE Software. Further analyses are performed by the use of MATLAB.

4 ACHIEVED RESULTS

4.1 Results of transient load and irradiance chances

In Fig. 3 results are given of a test applying by a step function of solar irradiance resulting in a nearly immediate rise of active power of the PV inverter followed by an immediate reduction in line voltage. In the linear regime of the static Q(U) characteristics this have to give rise to reactive power, according to the settings given by the TC time constant of the control system.

Smaller values of the Q(U) time constant leads to shorter periods the line voltage is above a given value, before it is compensated. The final value voltage value results from the delivered reactive power according to the DUT's static Q(U) characteristics, at the given grid impedance. All this measured step responses provided stable control conditions of the DUT.

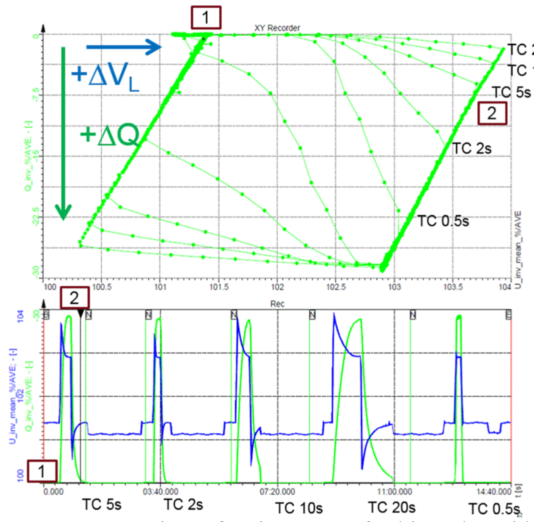

Figure 3: Transient of active power feed into the grid by the DUT forcing reactive power according to demanded Q(U) control at different parameter settings of TC 0.5, 2, 5, 10 and 20 seconds and thus compensate the line voltage rise. While the graphs in the bottom shows the measured line voltage (blue) and the produced reactive power by the DUT, the above graphs represents the same measurement data plotted reactive power Q versus line voltage V_L.

4.2 Results of real weather data performance

The requested active power of the DUT during an excerpt of a typical cloudy day in the Zurich area in April, as shown in Fig. 4 is performed by applying the alteration of the calculated current voltage characteristics of a crystalline silicon PV generator onto a DC amplifier according to the measured solar irradiance characteristics.

In Fig. 5 the measured produced reactive power is given for three TC parameter settings and without Q(U) control. The characteristics of the measured line voltage versus time is shown just below.

How effective Q(U) may reduce the voltage rise is illustrated in Fig. 6 and 7 by sorting the voltage measurement according the total time the line voltage exceeds a certain value shown in % of the nominal voltage, which is given in function of minutes.

In detail the analysis performed at a threshold of 102.8% of nominal voltage yield 45% of the time without Q(U) and 3.4% at TC of 20 seconds, only 0.3% at TC 5 seconds and never above at a TC of one second.

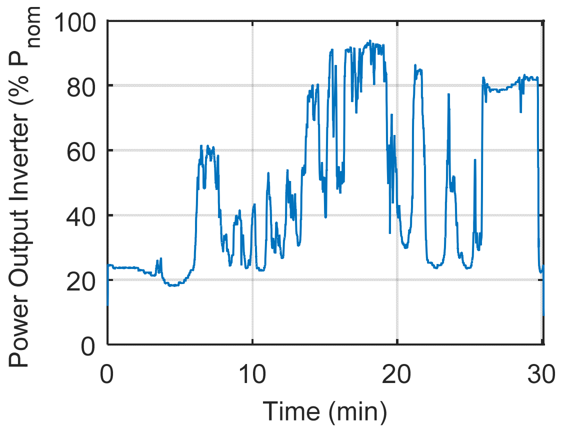

Figure 4: The shown active power feed-in by the PV inverter into the grid is the result of the applied solar irradiance characteristics in the HIL setup as a function of DC amplifier output.

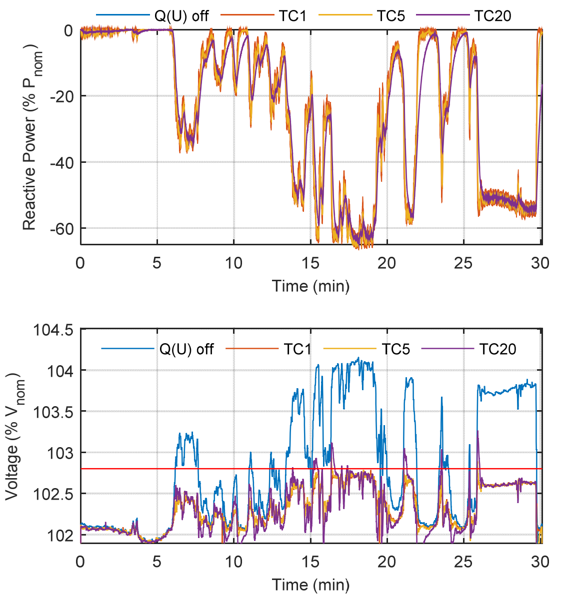

Figure 5: Thirty-minute voltage characteristics as a function of reactive power applied by a PV inverter during the same real solar irradiance conditions with parameter settings of 1, 5 and 20 seconds of the Q(U) controller and without Q(U) control.

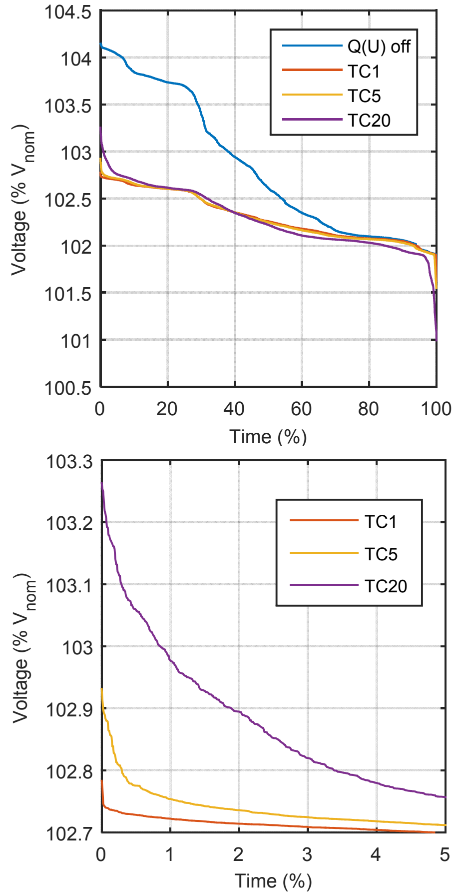

Figure 6: Voltage duration curve over 30 minutes as a function of reactive power applied by a PV inverter during the same real solar irradiance conditions with parameter settings of 1, 5 and 20 seconds of the Q(U) controller and without Q(U) control.

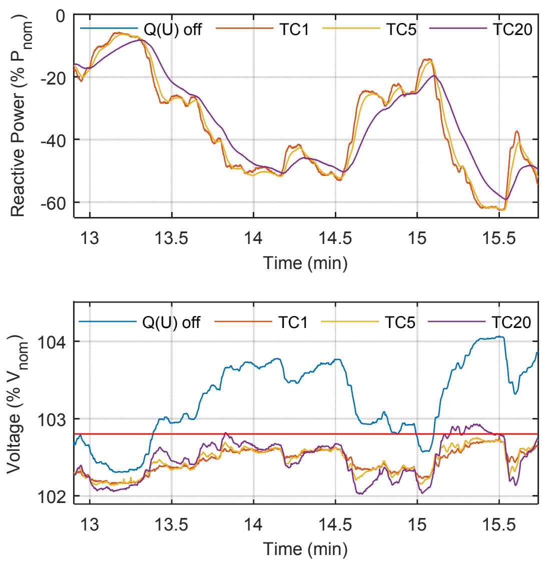

Figure 7: Three-minute voltage characteristics as a function of reactive power applied by a PV inverter during the same real solar irradiance conditions with parameter settings of 1, 5 and 20 seconds of the Q(U) controller and without Q(U) control.

4.3 Results including a substation

One solution to improve the DG voltage quality is the use of transformers to the next grid level with automatic operation of the OLTC to select the appropriate voltage at the output of the substation. If the voltage is higher than a certain threshold the OLTC will step down one interval as shown in Fig. 8. The implementation of a delay time of typ. larger 10 sec and algorithm to change voltage by only one-step, e.g., 1% of nominal voltage was intended as the base of a stable operation, not to activate the OLTC due to regular small fluctuations of irradiance. Larger steps of the tap-changer exceeding a regular smallest voltage interval will only occur at higher voltage changes, which will never be a results of Q(U) control activities. But what happened if the PV installer set the wrong sign of the static characteristics?

These assumptions and the theoretical work dedicated to the stability of Q(U), focusing on the inclusion of a dead time of the Q(U) control [7] leads to the test in the lab.

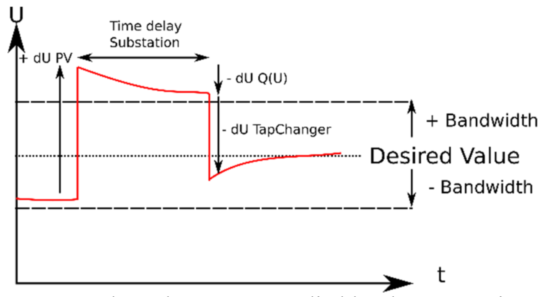

Figure 8: The voltage steps applied by the automatic tap changer after a certain delay time at the substation is superposed by the PV inverters automatic Q(U) control resulting in –dU Q(U).

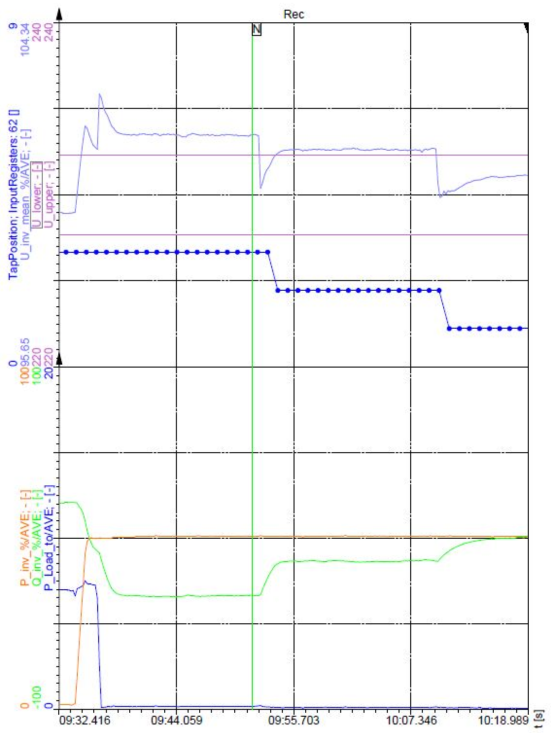

Figure 9: Voltage characteristics (blue) and the position of the tap changer (blue dots) shown in the top and the characteristics of the delivered reactive (green) and active (orange) power by the DUT at a time constant setting of 2 seconds together with a load loss (blue below).

As shown in Fig. 9 if the voltage is above the threshold it needs to step down for the transformer to stay in the voltage band, due to counter action of the Q(U) voltage control if the signs of the static Q(U) settings are chosen well.

In principle in most of the cases both actors the tap-changer and the Q(U) control will both work against voltage changes occurring due to irradiance changes over one day as seen in Fig. 10.

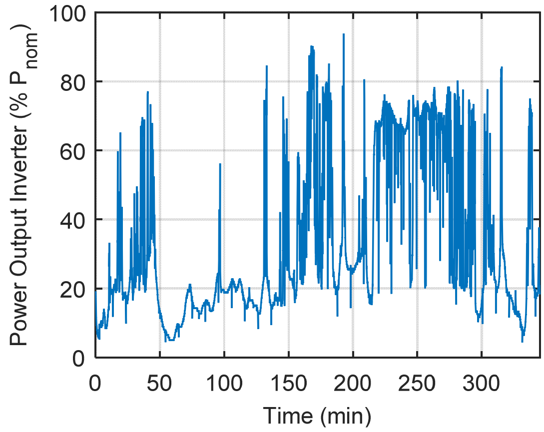

Figure 10: The shown active power feed by the PV inverter into the grid is the result of the applied solar irradiance characteristics over 350 minutes in the HIL setup as a function of DC amplifier output.

The result of this is that about 90% of that period the voltage is within a bandwidth of about 1% as illustrated by Fig. 12. In detail in Fig. 11 also the number of switching actions of the tap changer is seen with the threshold values at 99 and 101%.

Tab. 1 Duration in % of total period to be above/below the given voltage level around 100% including substation OLTC and Q(U) control.

in%	> 100.5%	>101%	<99.5%	<99
Q(U) aus	4.8	4.8	32.3	2.6
TC5	1.5	1.5	4	0
TC25	1.4	1.4	21.3	0.2

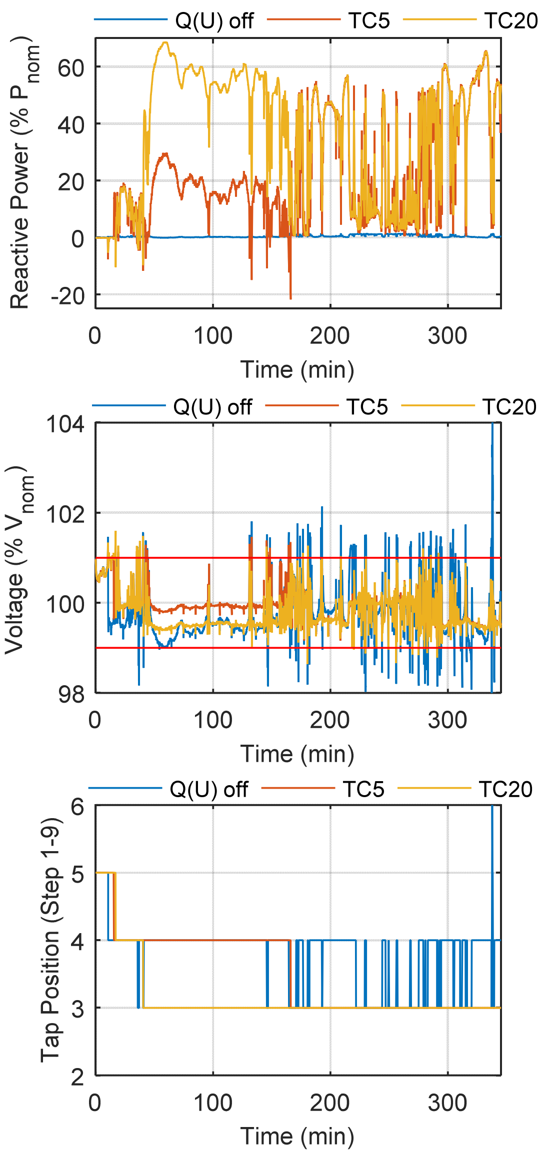

Figure 11: Three-minute voltage characteristics as a function of reactive power applied by a PV inverter during the same real solar irradiance conditions with parameter settings of 1, 5 and 20 seconds time constant TC of the Q(U) controller and without Q(U) control.

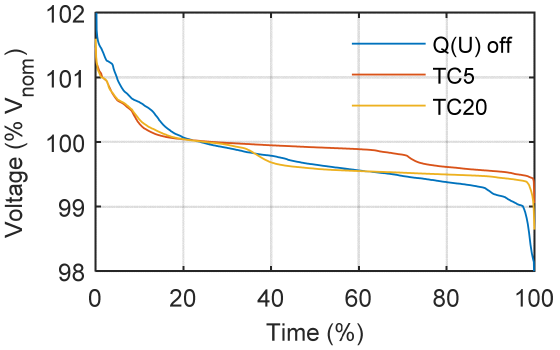

Figure 12: Voltage duration curve over 350 minutes including a substation and reactive power applied by a PV inverter during the same real solar irradiance conditions with parameter settings of 5s and 20s time constant TC of the inverters Q(U) controller and without Q(U) control.

4.4 Measured Oscillation of the line voltage

In principle oscillations expected only if at least to actors in a control loop work in the opposite direction. Like decreasing the voltage by the Q(U) control, due to a step up in irradiance, followed by an action of the OLTC, step down the voltage due to exceeding the threshold limit longer than the delay time.

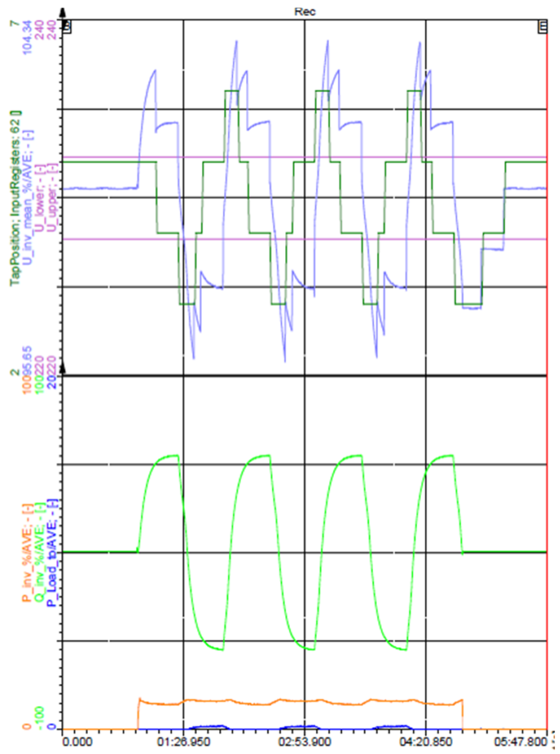

Figure 13: Opposite sign of static Q(U) characteristic settings results in oscillation of the line voltage with a time constant of about 20 second, which represents twice the delay time constant of the OLTC setting.

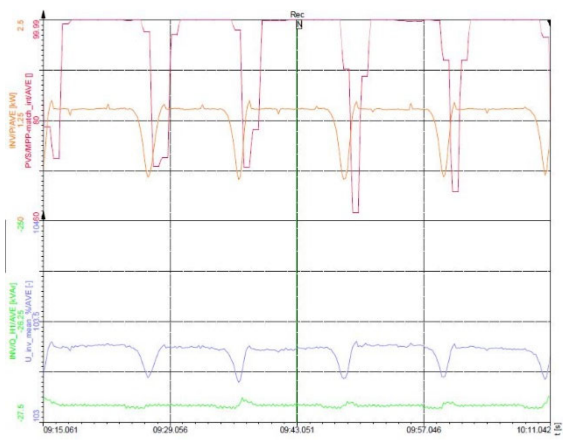

Figure 14: Small line voltage oscillations at a period of about 15 seconds at maximum reactive power and low active power and at the apparent power limit of the inverter performed by increasing the DC voltage to reduce the maximum power tracing efficiency of the PV generator current voltage characteristics.

5 RECOMMENDATIONS AND CONCLUSIONS

The very cost-effective method of reducing the rise of line voltage due to changes of solar irradiance and load was always stable at regular settings of the PV inverter parameters. Oscillation of the line voltage of several percent were found when the sign of the static characteristics of the reactive power demand is mixed up by the PV-installer or the PV inverter settings are hacked. Than the voltage rise is not compensated by the Q(U) but get progressively changed. Later only happen if the PV inverter is connected to a sub-station transformer equipped with an automatic controlled tap-changer interacting with the inverters control regime in a positive feedback mode.

It is recommended to the DG operator grid code to prescribe values of the PV inverter Q(U) time constant to be below 5 seconds resulting in reduced time intervals of overvoltage during the first moments when the Q(U) demands changes in the reactive power production.

It has to be paid attention how the time constant is executed by the inverter, as multiple definitions exist in different national grid codes. The time constant might be defined as the time reaching 1τ (63%) or 3λ (95%) of the required reactive power set point after a voltage step.

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REFERENCES

[1] F. Baumgartner, F. Carigiet, P. Korba; Swiss Federal Bureau of Energy, BFE-Contract No. SI/501370-01, Project CEVSOL; public annual Report 2016, 2017

[2] F. Carigiet, M. Niedrist, C. Scheuermann, and F. Baumgartner, “Case study of a low-voltage distribution grid with high PV penetration in Germany and simulation analyses of cost-effective measures,” Prog. Photovolt. Res. Appl., 2015

[3] F. Carigiet, F. P. Baumgartner, P. Korba, M. Niedrist; “Optimisation of the Load Flow Calculation Method of Low-Voltage Distribution Grids”, 33rd EU PV Conference; Amsterdam, Sept 2017

[4] F.P. Baumgartner, F. Carigiet, C. Messner, C. Seitl, T. Strasser, R. Bründlinger; “Stability of Photovoltaic Inverters Reactive Power Control by the distribution GRID voltage”; ISENEC conference, Nürnberg, July 2018

[5] F. Andrén, B. Bletterie, S. Kadam, P. Kotsampopoulos and C. Bucher, "On the Stability of Local Voltage Control in Distribution Networks With a High Penetration of Inverter-Based Generation," in IEEE Transactions on Industrial Electronics, vol. 62, no. 4, pp. 2519-2529, April 2015[6]

[6] A. Constantin and R. D. Lazar, “Open loop Q(U) stability investigation in case of PV power plants,” in Proc. 27th Eur. Photovoltaic Solar Energy, Conf. Exhib., Frankfurt, Germany, 2012, pp. 3745–3749

[7] O. Marggraf, I. Berber, B. Engel; “ Sichere Netzintegration mittels Q(U)-Regelung und rONT im Praxistest “; PV Tagung Staffelstein, März 2018