

VOLTAGE REGULATION (MV) BY MEANS OF Q(U) – SIMULATION AND MEASUREMENT ON A 12 MVA PV POWER PLANT

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ABSTRACT

Open loop reactive power (Q) control function of the local voltage (U) measured at the inverter's terminals is one possibility to comply with the BDEW's MV grid regulations [1] in Germany, while other countries are considering to apply this solution as well. A better understanding of the stability limits for such a control algorithm is required when applying it to large PV plants or PV dominated grids. A dynamic RMS simulation model of a big PV plant including $Q(U)$ control is developed. The model is compared with real life measurements in the PV plant and the local laboratory. Various study cases are further on performed in order to assess the voltage stability. An upper stability limit can be found depending on the grid connection parameters in the point of common coupling (PCC).

INTRODUCTION

In Germany one of the reasons for using reactive power control by PV plants is contained in the requirement of the BDEW MV guideline from Section 2.3, "Admissible voltage changes" [1]:

"Under normal operating conditions of the network, the magnitude of the voltage changes caused by all generating plants with a point of connection to a medium-voltage network, must at no junction point within this network exceed a value of 2 % as compared to the voltage without generating plants.

$$\Delta u_a \leq 2\% . "$$

The PCC voltage can be controlled, among other strategies, by setting the PV inverter to inject a certain amount of reactive power (inductive or capacitive) in the grid. This can be achieved either by setting a fixed reactive power level, a fixed power factor or by varying the reactive power injection depending on a measured voltage value. The voltage measurement may be the local inverter voltage (open loop control) or the remote PCC voltage (closed loop control). Using remote sensing implies additional measurement equipment in the PCC and eventually communication devices which may be costly as shown in Figure 1. A cheaper alternative is the open loop $Q(U)$ control algorithm where each inverter measures its own terminal voltage and calculates the corresponding reactive power contribution as in Figure 2.

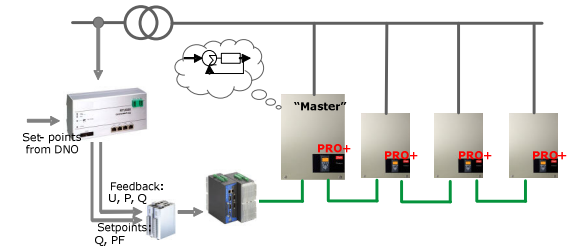


Figure 1: Closed loop control of a PV power plant

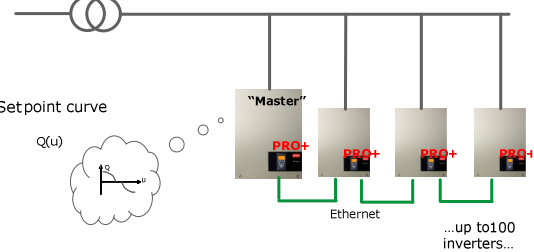


Figure 2: Open loop control of power-plant by means of $Q(U)$. No measurement device is installed in the PCC at the busbar of the transformer unit (LV or MV).

METHOD DESCRIPTION

The operating principle of the open loop $Q(U)$ control algorithm may look as the one in Figure 3.

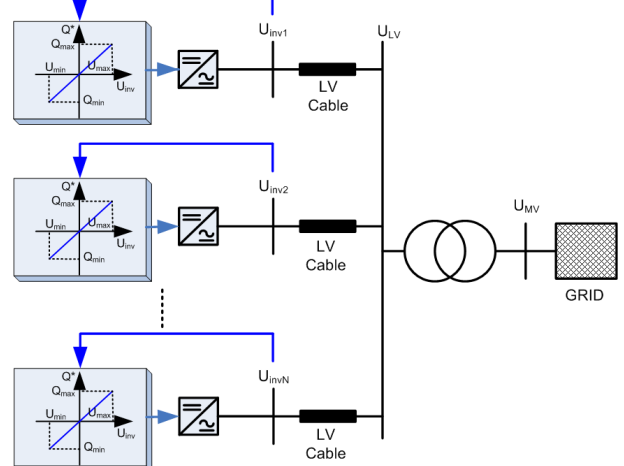


Figure 3: Principle of a $Q(U)$ table based control algorithm

The $Q(U)$ characteristic can be preprogrammed in the Danfoss TLX inverters by defining multiple $Q=f(U)$ operating points. Further in the article, for simplifying reasons, it has been considered a $Q(U)$ characteristic

defined only by two operating points $\{Q_{\max}, U_{\min}\}$ and $\{Q_{\min}, U_{\max}\}$. The slope m of the $Q(U)$ characteristic represents the sensitivity of the reactive power controller versus voltage changes. It is defined as below:

$$m = \frac{\Delta Q}{\Delta U} = \left| \frac{Q_{\max} - Q_{\min}}{U_{\max} - U_{\min}} \right|$$

Due to the fact that open loop control is a feedforward compensation a too high gain (m) may lead to instability situations. Unwanted voltage oscillations may appear on the network with negative effects on the power grid (flicker, over/under voltage etc). Several $Q(U)$ characteristics are plotted in Figure 4 for increasing sensitivity (m) from 10 to 30.

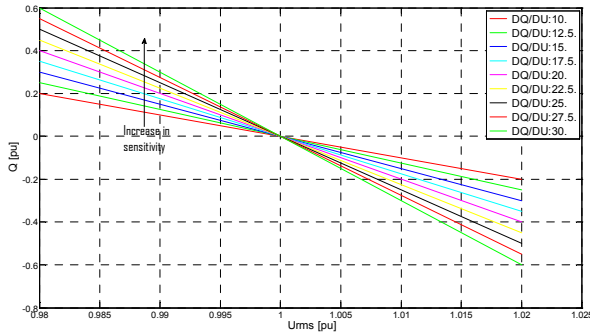


Figure 4: $Q(U)$ characteristics for different slopes
A dynamic RMS simulation model is implemented in Power Factory DIgSILENT and is based on the open loop control algorithm described in Figure 3. The model block diagram is shown in Figure 5.

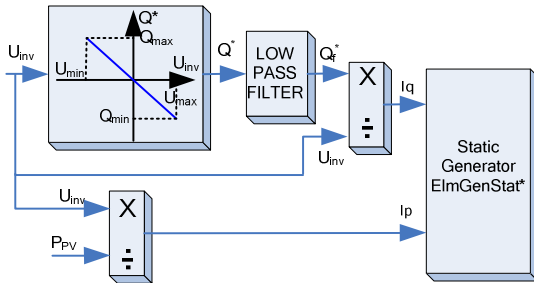


Figure 5: Inverter unit $Q(U)$ control algorithm in simulation

The inverter voltage at the busbar is used as input to a block containing the $Q(U)$ characteristic. A resulting reactive power reference Q^* is obtained. According to the german MV guideline [1], a settling time constant τ_s must be made available to the user with values varying between 10 and 30 seconds. This is implemented by using a low pass filter block on the reactive power reference branch, resulting the filtered reactive power reference signal Q_f^* . The reactive current component I_q is calculated by dividing Q_f^* by the terminal voltage U_{inv} . Similarly the active current component I_p is computed based on the input PV power. The inverter generates the output AC currents instantaneously to the power grid using

a builtin Power Factory model (ElmGenStat*). This assumption is valid since the time constant of the inverter is much smaller than the settling time parameters of the reactive power (higher than 10 s).

BUSENWURTH PHOTOVOLTAIC POWER PLANT

The PV power plant studied in this paper is located in Busenwirth, Germany, see Figure 6. The electrical diagram of the power plant is depicted in Figure 8. The plant is divided in seven subsections each of them connected to a LV/MV transformer and with 120 pieces of the TLX 15k PRO+ string inverters ($S_r = 15kVA$). These subsections are connected through a MV cable to the main transformer to the HV network approximately 5 km away.



Figure 6: Busenwirth 12 MW PV power plant from the air, courtesy of Möhring Energie GmbH [2].



Figure 7: Detailed look on a part of the 12 MW PV power plant equipped with TLX inverters, courtesy of Möhring Energie GmbH [2]

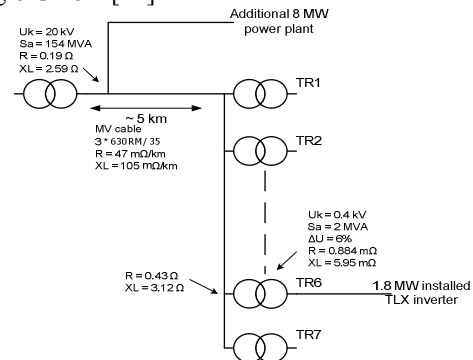


Figure 8: Schematic over the 12 MW power plant in Busenwirth, Germany

For each section of the plant (TR1 to TR7) there is an electrical schematic built in Power Factory as in **Figure 9**. Due to practical limitations, model aggregation has been applied to a block of 10 inverters. They are represented in the circuit by a single PV generator with a scaled rated power. This simplification can be done as long as the aggregated inverters are placed relatively close to each other with negligible cable lengths in comparison to the other components (transformers and LV, MV cables).

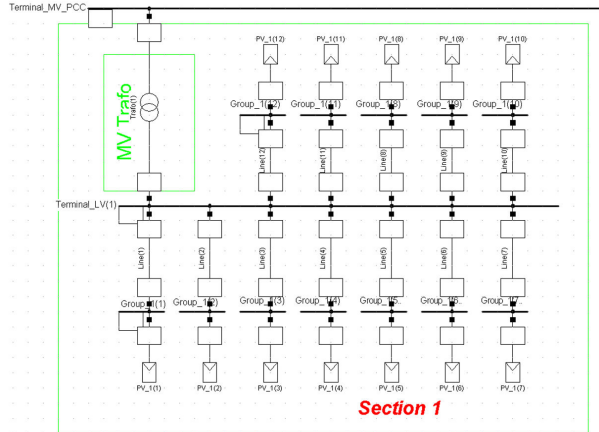


Figure 9: Schematic of one PV plant section in Power Factory

TEST RESULTS AND COMPARISON WITH SIMULATION

Test on a 10 inverter group in laboratory

A preliminary test has been performed in order to assess the performance of the dynamic RMS simulation model in the local laboratory shown in Figure 10. A total of 10 Danfoss TLX inverters are set to open loop Q(U) control mode. The dQ/dU sensitivity is applied in steps as shown in Figure 11. A settling time constant $\tau_s = 10s$ is used.

The results are shown in Figure 12 to Figure 15.

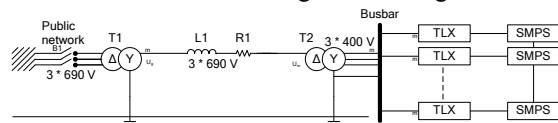


Figure 10: Schematic for the 200 kVA test facility at Danfoss Solar Inverters

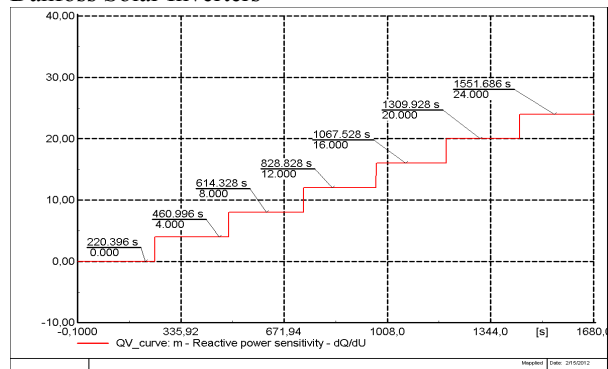


Figure 11: Applied sensitivity m during laboratory test. The voltage at the LV side of the LV/MV transformer is shown in Figure 12. It can be seen that the system is

marginally stable for a value $m = 20$ and becomes unstable for $m = 24$. Similar performance is observed both in simulation and measurements. The voltage oscillations are deviating from the steady state value by $\pm 2\%$. The RMS phase currents are shown in Figure 13. An increase in the magnitude of the current is observed mainly due to the increase in the reactive current component. The reactive power is displayed in Figure 14. A steady state error is visible, mainly due to the absence of the inverter's output filter in the RMS model. The active power output is shown in Figure 15. A small decrease in the power is seen in the measurements if reactive power control is active. This small relative error accounts to less than 2% of the initial active power.

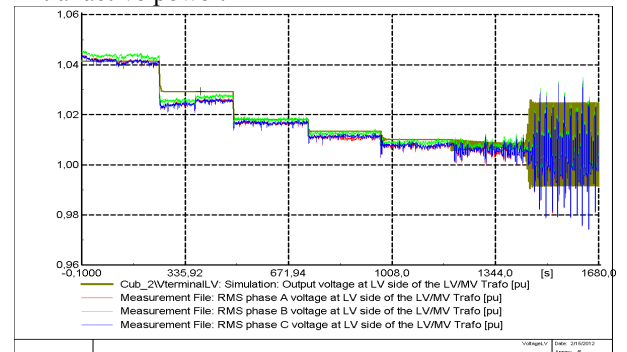


Figure 12: RMS voltage at LV side of the LV/MV transformer (T2)

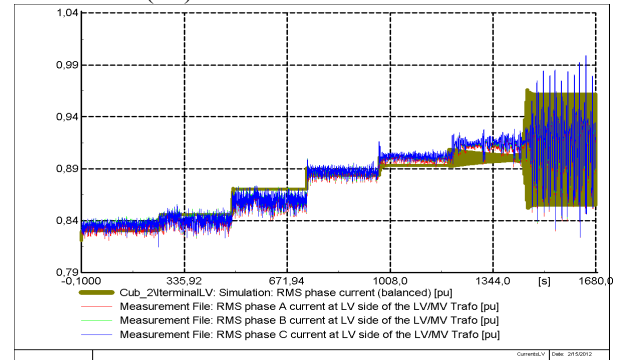


Figure 13: RMS phase currents at LV side of the LV/MV Transformer (T2)

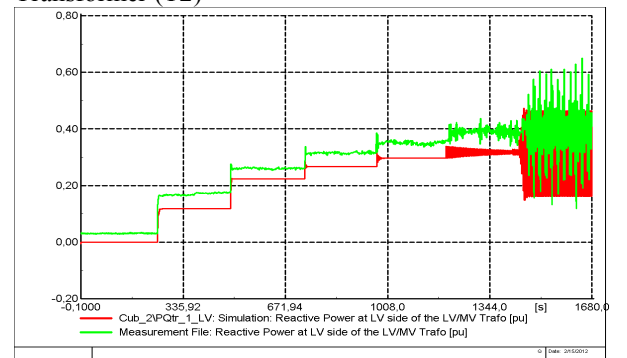


Figure 14: Reactive power at the LV side of the LV/MV Transformer (T2)

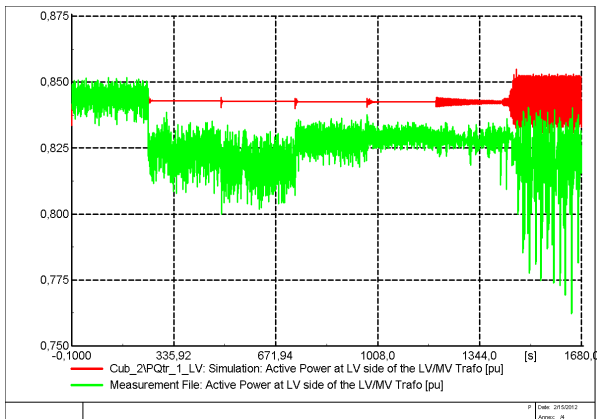


Figure 15: Active power at the LV side of the LV/MV Transformer (T2)

Test on a 1.8 MVA PV plant section

A PV plant test has been performed in order to detect the stability limit of the open loop control. This is done by setting one 1.8 MVA PV section in open loop control mode while keeping the reactive power injection from the other sections to zero. The dQ/dU sensitivity is modified in steps as shown in Figure 16. A settling time constant $\tau_s = 10s$ is used. A PV active power output of the entire PV plant of about 50% has been recorded at the moment of testing. The RMS voltages (measured and simulated) are shown in Figure 17 and Figure 18.

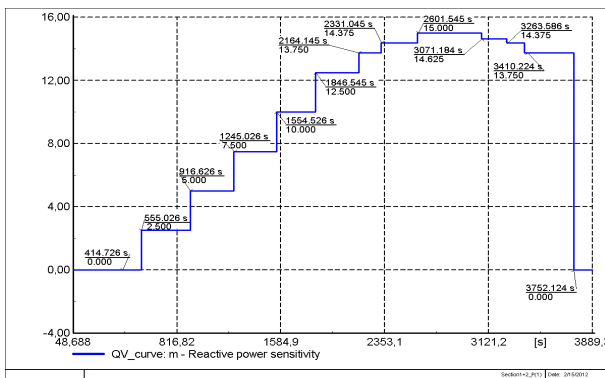


Figure 16: Applied sensitivity (m) during PV plant test

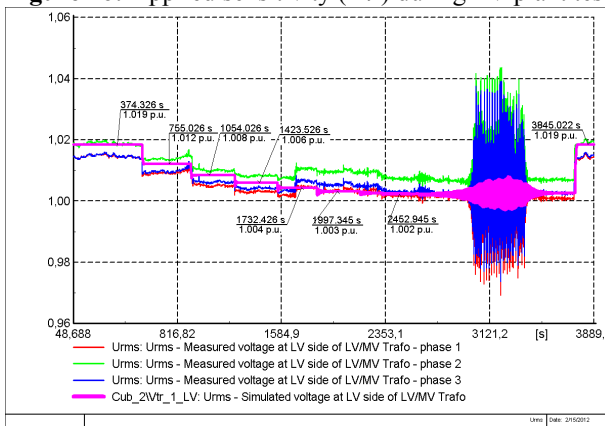


Figure 17: Measured and simulated voltage at the LV side of the LV/MV transformer

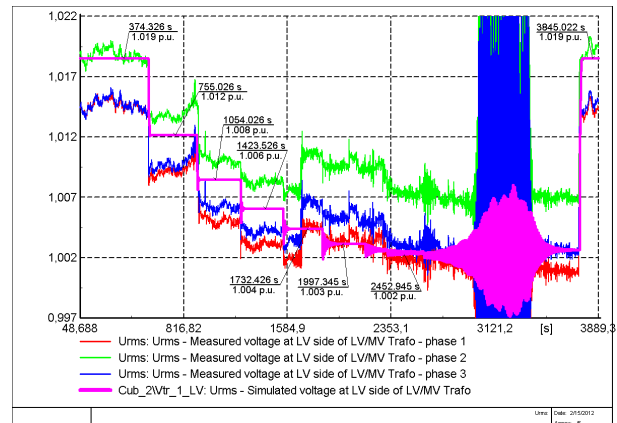


Figure 18: Rescaled view of Figure 17

The voltage measurement is a good indicator of the stability of the open loop controller. It is obvious from the results that for sensitivity values m higher than around 14.5 one PV inverter section of 1.8 MVA will become unstable. Furthermore, high oscillations varying from +4% to -3% from the steady state value are seen in the measured voltage of the LV busbar of the transformer. A lower level of oscillations is present in the simulation results, still with clear indication of instability. Further simulations show that when applying the Q(U) control algorithm to the entire plant the maximum stable sensitivity decreases slightly (around 12.5). Further simulations show that the system is more stable when using higher values for the settling time constant.

CONCLUSIONS

A simple dynamic RMS simulation model is implemented in Power Factory DiGSILENT and tested against real life situations. Sufficient correlation between simulation and measurements is found in order to assess the limit of stability for the open loop Q(U) control algorithm in a laboratory environment and in a big PV plant. It is possible to estimate the operating limits of the open loop controller for specific PV plants by means of simple dynamic simulation and using known grid connection parameters (S_k and X/R ratio).

REFERENCES

- [1] BDEW, June 2008, "Technical Guide – Generating Plants connected to the Medium Voltage Network".
- [2] <http://www.moehring-energie.de>