

## SUPERORDINATE VOLTAGE CONTROL IN SMART LOW-VOLTAGE GRIDS – LABORATORY AND FIELD TEST RESULTS

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### ABSTRACT

*Voltage control in low voltage grids is usually done using decentralized voltage control devices as on-load-tap changers or line voltage regulators, Volt/VAR-characteristics of infeeders or batteries. The application of a centralized superordinate voltage control strategy in low-voltage grids can help to both keep grid voltage within the limits given by the standards and raise the number of installed PV-generation without additional grid extension. The proof-of-concept of the superordinate voltage controller realized in the grid integration laboratory at TUM and the implementation and potential of the controller in a real low-voltage grid will be presented in the following paper.*

### INTRODUCTION

Future distribution grids will have to be able to provide grid access to prosumers and to fulfill the power quality specifications given in the DIN EN 50160. Both targets should not collide with the principles of a reliable and economical power supply. [1]

Taking advantage of controllable distribution grid utilities (PV-and battery-inverters and line voltage regulators LVR), existing infrastructure could be used to contain power quality within its limits without additional grid extension. The controllable inverters (PV-and battery-inverters and LVR) are provided with standard features for voltage control, e.g. voltage dependent reactive power feed-in. In addition they could receive reactive power set points transmitted by a superordinate controller, if necessary. The superordinate controller is monitoring all relevant grid parameters gathered by the active utilities. By additionally linking the superordinate controller to the control center of the grid operator, supervisory control and data acquisition (SCADA) capabilities for the low voltage distribution grid is enabled, which allows easy monitoring and manual input. Such a low voltage distribution grid would offer smart-grid functionalities (communication, power quality control, virtual power plant operation).

### RESEARCH PROJECT VERTEILNETZ 2020

The results are gained during the government-funded joint research project “Verteilnetz 2020”, including partners from other research institutes (Power Electronics: Institute ELSYS, TH Nürnberg) and industry (distribution grid operator: infra Fürth GmbH; Broad-Band-Powerline: PPC AG; Automation and Telecontrol: IDS GmbH;

Batteries: BMZ GmbH / Grass Power Electronics GmbH; PV-Inverters: KACO New Energy GmbH, Line Voltage Regulators: A-Eberle GmbH / Grass Power Electronics GmbH).

During the research project, a continuously stepping line voltage controller has been developed which is able to additionally supply reactive power at its primary side (functionality of UPFC). PV-inverters with improved settling time of reactive power control (~500 ms) and possibility to receive external reactive power set-points have been designed. A powerline communication robust against emitted interference from power electronics has been developed. Moreover, different concepts for superordinate control have been investigated [7, 9]. The project schedule contains simulations, laboratory tests and a field test in the low voltage grid Unterfarnbach/Fürth. The follow-up project “Smart Grid Cluster” will continue the research based on the results and hardware installation/development that have been already done throughout the past four years.

### CONCEPT OF SUPERORDINATE VOLTAGE CONTROL IN A LOW VOLTAGE GRID

The main task of the central controller is to keep voltage within the limits of 1.1 p.u. and 0.9 pu respectively [1].

It’s design has been inspired by the smart grid traffic light concept of the BDEW [2] and [3].

All measurement data are continuously monitored by the superordinate controller. During uncritical grid operation (corresponding to the green phase) the system is operating in an autonomous mode – all controllable devices (PV, batteries, LVR) operate according to decentralized voltage control already used in present-day low-voltage grids.

If violations have been detected (corresponding to the yellow phase) the controller changes to controlled mode operation. Set points for the controllable devices are computed according to a hierarchical control strategy.

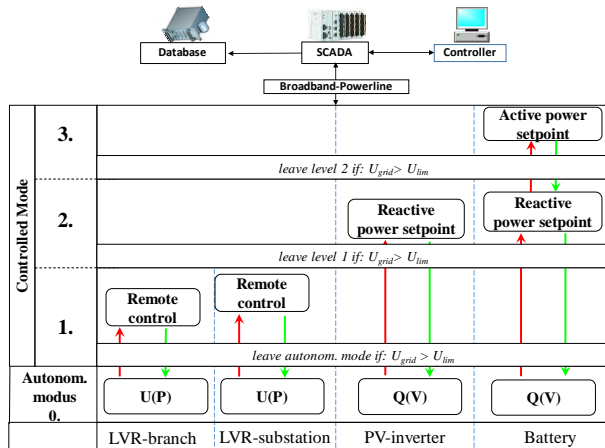
#### Autonomous Mode

The autonomous mode is active when grid voltages monitored by the controller stay within the predefined limits. In this mode no action by the controller is necessary and all controllable units operate according to their standard characteristic curves (Q(V) for PV- and battery inverters or load-dependent voltage characteristics for LVRs). The transmitted amount of data can be reduced.

In case of communication failures all controlled devices will also operate according to the autonomous mode.

## Controlled Mode

Whenever autonomous-mode counteractions have failed, or were not sufficient for keeping voltages within the predefined limits, the system switches to the controlled mode. The effectiveness of the different control options, as there is voltage control by means of reactive power feed-in (inverters) or by influencing overall grid voltage with the LVRs is considered. (see Figure 1).



**Figure 1:** Control levels of the central controller

### Level 1:

First-level voltage control is done using the LVR. If there is more than one device installed, a sensitivity analysis is assigning all grid nodes to each LVR.

As an example: a line voltage regulator installed in a branch with overvoltage problems due to high PV-generation will be considered first for receiving new voltage set-points. If this line regulator is not capable of reducing voltage sufficiently, in the next control step the LVR placed at the substation will receive voltage set-points to lower overall grid voltage [6].

### Level 2:

If the voltage is still violating the predefined limits, the remaining controllable inverters (PV- and battery inverters) are used to feed in reactive power for voltage regulation.

Considering an inverter dimensioning:

$$S_{r,inv,AR4105} = \frac{P_{DC,peak}}{\cos\varphi=0,9} \quad (1)$$

every inverter can offer a surplus of reactive power compared to the Q(V)-characteristic suggested from AR 4105 [4].

$$Q_{max,AR4105} = \sqrt{S_{r,inv,4105}^2 - P_{DC,peak}^2} \quad (2)$$

$$Q_{actual} = \sqrt{S_{r,inv,4105}^2 - P_{actual}^2} \quad (3)$$

$$Q_{actual} > Q_{max,AR4105} \text{ for } P_{DC} < P_{DC,peak}=1.0 \text{ pu} \quad (4)$$

Due to efficiency losses and high PV-generation during summer time  $P_{DC,peak}$  can be assumed to 0.8 pu [5] and the potential for additional Q is given.

In order to determine a ranking for the most efficient use of reactive power a sensitivity analysis for voltage dependent reactive power control is calculated in advance for every actively monitored node [8]. Hence, every inverter will get a corresponding reactive power set point to affect detected voltage violations, with respect to its effectiveness for voltage control at a specific node.

### Level 3:

In level 3 batteries are used for voltage control by adjusting their active power feed-in / consumption.

Even though batteries would have a higher impact on grid voltage in low-voltage-grids (R/X ratio > 1), the preset charging strategy of the batteries should only be overruled if absolutely necessary. Therefore this method is being used in the subordinated level 3.

The charging strategy is computed by a neural network considering peak shaving and an optimum for own-consumption, as well as increased battery lifetime.

*Note: Level 3 will not be part of the results presented below.*

## LABORATORY RESULTS

The general approach of a superordinate control strategy has been realized as a proof of concept at the grid simulation laboratory which has been planned and installed during the last years at TUM.

### Set-up of the Laboratory Simulation Network

In the lab different voltage control strategies can be investigated.

In order to simulate real power cables, their physical parameters (R, L and C) have been modelled using adjustable concentrated elements. In total, six grid segments (each representing an emulated power cable) can be interconnected as a radial grid or a star grid. (see Figure 2).



**Figure 2:** Grid simulation laboratory

The laboratory grid is supplied by an AC-source with 45 kVA. Magnitude and shape of the AC-source's secondary side voltage can both be adjusted. Due to this functionality it is also used as a LVR.

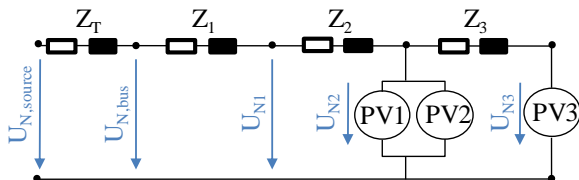
PV-Inverters of an overall connected rating of 60 kVA (manufacturers: KACO and SMA) can be connected to different nodes of the laboratory grid. They are supplied by controllable DC-sources that deliver any desired PV-Profile.

Furthermore a three-phase AC-load (P and Q adjustable independently for each phase) can be used in order to investigate unsymmetrical behaviour of the devices.

The results discussed in this paper have been obtained using the test set-up depicted in Figure 3:

A transformer impedance  $Z_T$  ( $L = 0,3$  mH representing a 50 kVA low-voltage transformer) has been connected in series with three segments of the concentrated elements ( $Z_1, Z_2, Z_3$ ). The segments impedances have been set to  $R = 0,350$  m $\Omega$  and  $L = 0,4$  mH (representing a NAYY 4x150 mm<sup>2</sup> cable of 1480 m each).

To be mentioned: due to limited power of the AC-source, it has to be made a trade-off between emulating real low-voltage grid conditions (e.g. typical cable types and lengths) and desired considerable voltage raise higher than 1.1 pu over the concentrated elements. Therefore, the above described cable length is a rather untypical dimension for low voltage grid segments.



**Figure 3:** Laboratory set-up for testing the central control

The used inverters are:

PV1: 9 kVA (P/Q controllable)

PV2: 10 kVA (used for voltage raise)

PV3: 15 kVA (used for voltage raise)

PV1 is used for Volt-VAR control. It is both able to use a characteristic curve and direct set-points for reactive power control. The settings according to the two operation modes are transmitted using the SCADA approach (see also Figure 1). Broadband powerline is not used in the lab – the devices (inverters and DC-sources) are controlled using LAN and Modbus TCP. PV2 and PV 3 are only used to raise up the voltage in the test grid ( $\cos\phi = 1$ ).

The controller algorithm has been implemented using the software LabVIEW. Grid voltages (for observing voltage violations) and set-points (for the controlled mode) can be transmitted every second. This setting has been adjusted according to the minimum achievable transmitting-time in the field test area.

## Results

In our case (neglecting voltage raise from the medium voltage level) the voltage limit that should not be exceeded has been set to 1.04 pu (239 V) with respect to results from previous studies [5]. In order to avoid undervoltages, the lower limit has been set to 0.95 pu (220 V).

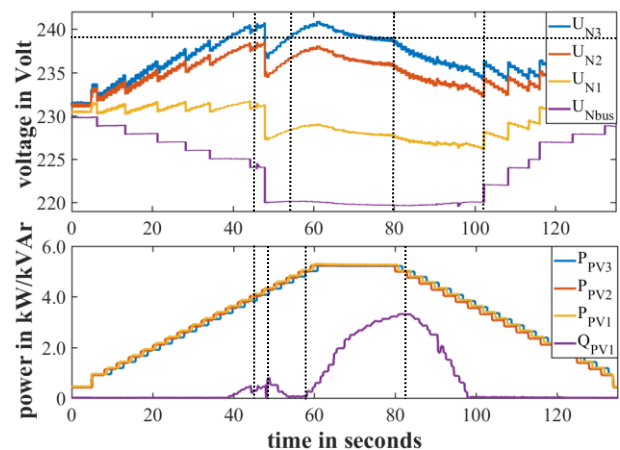
The DC-sources received power set-points describing a ramp from 500 to 5000 Watts (minimum starting power in order to avoid the start phase of the inverters at the beginning). The time shift between each set point for each of the three sources (see Figure 4) has been set to 1 second. All inverters work in constant voltage mode.

Due to the serial connection of the laboratory grid, highest voltages are expected for PV3.

Without any control and considering a  $\cos\phi = 1$  for all PV-inverters, the obtained maximum voltage for PV3 is around 256 V and hence significantly higher than 1.1 pu.

## Autonomous mode

In the autonomous mode, the LVR is controlling its own secondary side ( $U_{N,bus}$ ) following a load dependent voltage characteristic resulting in voltage steps of 1 V. PV1 is operating according to the Q(V) standard characteristic recommended in AR 4105 and [10].



**Figure 4:** Voltage and power curves obtained in the lab

At  $t \sim 40$  s the voltage of PV2 (connected to  $N_2$ ) is exceeding 237 V (1.03 pu) and reactive power is fed in according to the pre-defined Q(V)-characteristic .

## Switching process from auton. to controlled mode:

As voltage is still raising the mode is switching to the controlled mode at  $t = 45$  s. PV1's last reactive power value before switchover (according to previous Q(V)) is now set as a fixed value and remains constant in the first time-step.

## Controlled Mode - Level 1:

The LVR (AC-source) is now controlling the violated voltage  $U_{N3}$  resulting in a voltage drop of another 5 V to 220 V. This represents also the lower limit for overall grid voltage (0.95 pu) – the LVR is not allowed to step down anymore and Level 2 is activated.

### Controlled Mode - Level 2:

At  $t = 48$  s PV1 reduces its reactive power following a PT1-behaviour (due to the stepping of the LVR voltage  $U_{N3}$  is no more violating the limits and Q is reduced).

At  $t = 54$  s the next voltage violation at  $U_{N3}$  occurs (controller receives the value up to 1 second delayed).

From  $t = 58$  s PV1 is reacting to the new controller output signals of the controller and increasing its reactive power. The resulting curve  $Q_{PV1}$  is showing PT1 behaviour again.

Due to the time delay of communication node voltage  $U_{N3}$  is slightly violating the preset limit of 1.04 pu but reaching and keeping the desired set-point of 1.04 pu at  $t = 80$  s.

At  $t = 80$  s voltage  $U_{N3}$  is beginning to decrease again resulting in a decrease of PV1's reactive power output to 0 kVAr at  $t = 98$  s (transition condition for stepping down to level 1).

### Controlled Mode – Switch-back to Level 1:

At  $t = 102$  s the controller steps back to level 1 and hence the voltage  $U_{N3}$  is still decreasing the LVR (AC-source) is stepping up its secondary side voltage again until it reaches its secondary side voltage before switching over to the controlled mode (transition condition for leaving controlled mode again).

The switch-back to the autonomous mode is not shown in fig. 4.

## FIELD TEST RESULTS

### Field Test Set-up

The control strategy described above is going to be applied for the low voltage grid Unterfarnbach, part of the infra Fürth power grid, in a field test.

Unterfarnbach is supplied by two substations of 630 kVA each. Around 400 consumers and around 50 PV-plants are connected to the low voltage grid. With a peak load (without infeeders) of about 500 kVA and an installed PV-capacity of around 1 MW, the grid is ideal for analyzing the impact of high PV-penetration on line-loading and voltage problems.

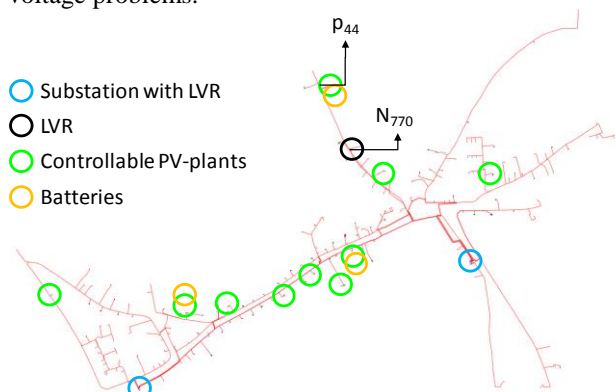


Figure 5: Field test set-up

In the field test area (see Figure 5) stepless LVR (2x 630 kVA at the substations / 1x 250 kVA), 10 PV-inverters

with functionality of both characteristic curve mode (e.g.  $Q(V)$ ) and direct set point mode (in total 500 kVA) and 3 batteries (30 kW / 30 kWh each) will be installed.

By additionally linking the superordinate controller to the control-center of the grid operator, supervisory control and data acquisition (SCADA) capabilities for the low voltage distribution grid are enabled (this is done using broadband-powerline technology).

During summertime at grid node p44 grid voltage up to 250 V can be observed due to an installed PV-capacity of 180 kW<sub>p</sub> at the end of the branch (not depicted in Figure 6).

### Measurements

The measurement data has been analysed for both November (considerable high solar irradiation) and December 2018 (installation of LVR). For this paper, only a short extraction can be presented.

The  $Q(V)$ -characteristic of the inverters was not activated for the shown results.

### Voltage Curves in the Uncontrolled Grid

Figure 6 shows the voltage curve for the sunniest day during November / December 2018 at grid node P<sub>44</sub> (highest absolute values for all 21 checked devices).

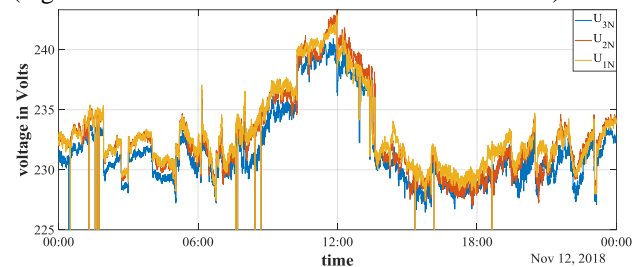


Figure 6: Voltage curve for p<sub>44</sub> (clear sky)

As it can be seen, even in November voltages of above 244 V (1.06 pu) are reached at noon. This will be even worse during spring and summer.

Measurements are also shown for the day with highest fluctuation in PV-generation (high gradients in produced PV-power due to cloud course).

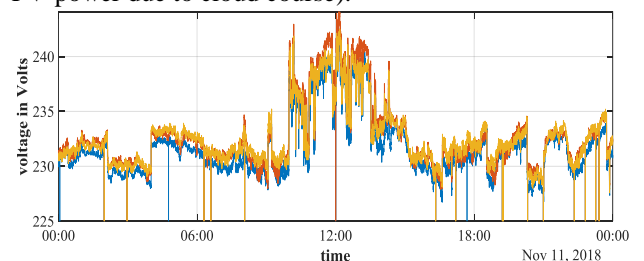


Figure 7: Voltage curve for p<sub>44</sub> (unsettled day)

Again, the obtained voltage curve for P<sub>44</sub> day is depicted in Figure 7. The maximum voltage is similar to days with clear-sky solar irradiation. However, the higher fluctuation of the node voltage can be seen by comparing Figure 6 and Figure 7.

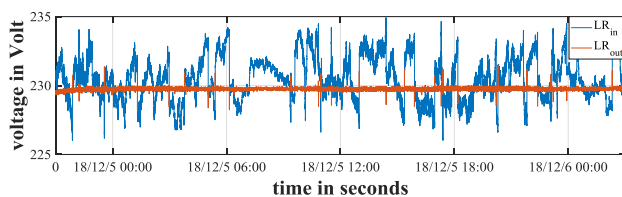
These voltage profiles will be used in the future for the tuning of the superordinate voltage controller in order to prevent oscillation of the controller.

### Influence of Line-Voltage-Regulator on Grid Voltage

Finally, first results from the LVR installed at node N<sub>770</sub> in the field test area shall be presented.

It is able to control its secondary side voltage to a fixed set-point (e.g. 1.0 pu) or by using load-dependent voltage characteristics (V(P)). Both methods can be adjusted and modified by the central controller.

Figure 8 shows the primary and secondary side voltage of the LVR. The set-point for the secondary side voltage (LR<sub>out</sub>) has been set to 1.0 pu.



**Figure 8:** Effect of the LVR on grid voltage

As one can see, the secondary side voltage is controlled almost to 1.0 pu. Only a small voltage ripple of 0.2 V remains.

The LVR has a maximum stepping capacity of  $\pm 0.05$  pu ( 11.5 V). Therefore, it could help to improve the voltage at P<sub>44</sub> significantly.

### CONCLUSION

The concept of a centralized superordinate voltage controller, its different modes (autonomous and controlled mode) and advantages compared to decentralized Volt-VAR control have been presented.

The proof-of-concept of the controller was realized in the grid simulation lab at TUM showing promising results for avoiding voltage violations and increasing PV-penetration in low voltage grids.

In future work, the tuning of the controller has to be improved concerning also fast voltage fluctuations in order to prevent it from oscillating. The controller for the field test (using also LabVIEW and the same control approach) will be designed.

Interactions of the line voltage regulator with the broadband powerline communication were observed and have to be resolved in order to guarantee a stable communication.

The presented results have been obtained during the government-funded project “Verteilnetz 2020”.

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