DECENTRALIZED VOLTAGE CONTROL IN 20 KV DISTRIBUTION GRIDS BY CONTROLLING REACTIVE POWER OF INVERTERS

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ABSTRACT

Decentralized generation units are capable to influence the voltage in the 20 kV-distribution grid by a controlled reactive power feed-in. In this paper different control characteristics and their impact on the 20 kV-medium voltage (MV) grid are presented. The focus in the simulation scenarios was the comparison of an active factor cosφ(P)-control characteristic with a reactive power/voltage characteristic Q(V). For the simulations a real 20 kV-MV-district was reproduced. The photovoltaic generation and load profiles were measured in this district and used in the simulation. So the simulation results could be aligned with the reality for the used cosφ(P)- and Q(V)-control mode and the effects of different parameterisations have been calculated. Furthermore, the influence of the control modes on the grid losses over a whole year could be considered. In addition, it was differentiated between a workday and weekend to cover different load situations. Due to this fact, this paper illustrates the simulation results for a single weekday in summer and winter. The investigation shows that decentralized generation units operating with a reactive power control can strongly impact the voltage level in a MV-district.

INTRODUCTION

The large amount of installed decentralized generation capacity makes it increasingly difficult for the distribution system operator (DSO) to control the voltage in the MV grid. The installed generation power in many MV grids of the LEW Verteilnetz GmbH (LVN) is considerably higher than the peak load.

The LVN is a DSO in southern Germany. In its supply area there are 64,000 decentralized generation units with an installed generation capacity of 1,756 MW (base end 2013). The highest share with 1,450 MW have photovoltaic generation units (PV), followed with a larger distance by biogas with 169 MW (cp. figure 1). This generation capacity has to be compared with a winter peak load of 1,800 MW and 900 MW in summer.

In Figure 1 the development of the connected generation capacity in the LVN grid since the introduction of the Renewable Energy Sources Act (EEG) is shown. The voltage in MV distribution grids is normally controlled by on load tap changers in the HV/MV transformer substations. The European Standard EN 50160 [1] requires a voltage range of ± 10 % of the nominal voltage on the customer side. Due to the mix of consumer load and many distributed energy generation plants, the voltage variations within the distribution grid are increasing.

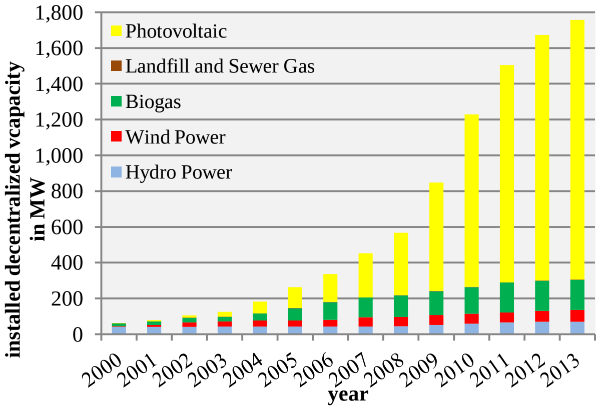

Figure 1: Development of decentralized generation capacity in the LVN grid.

According to the BDEW technical guideline “Generating Plants Connected to the Medium Voltage Network” [2], and the Cenelec Technical Specifications TS 50549 -1 [5] and TS 50549-2 [6] generation units shall be capable of participating in reactive power control to reduce the effect of the power feed-in on the voltage. Different control modes are defined in the standards [2, 5, 6]. The investigated control modes are a fixed active factor cosφ or an active factor cos$\varphi(P)$ in the range between $0.95_{\text{underexcited}}$ and $0.95_{\text{overexcited}}$ (according to [2]). Another control mode is a reactive power/voltage characteristic $Q(V)$. In the planning process of new generation plants the DSO specifies the control mode which has to be applied in the generation plant.

Since fixed cosφ and cos$\varphi(P)$ are well established methods in the LVN grid, there is a lack of practical experience with the $Q(V)$ control mode. The DSO is obliged to provide clear specifications concerning the reactive power behaviour of decentralized generation plants. In this paper, therefore, different control technologies for generation units - $Q(V)$ and cos$\varphi(P)$ - are compared and analysed simulative. Furthermore, the simulation results are verified with measurements in the field to compare the effects of the control modes in theory and praxis. Thus, this paper investigates the effects on the grid voltage and losses due to generation units operating with the same reactive power control technology in the MV grid.

EFFECTS OF DECENTRALIZED REACTIVE POWER GENERATION ON THE GRID

The technical standards mentioned above [2, 6] define clearly, that decentralized generation units have to take part in the voltage control at the MV-district during the feed-in of electrical energy. The decentralized generation plants (DG) are able to influence the voltage by consumption or feed-in of reactive power. Figure 2 illustrates schematically how the consumption of reactive power (dashed line) influences the voltage in the MV grid in comparison to the pure active power feed-in (continuous line).

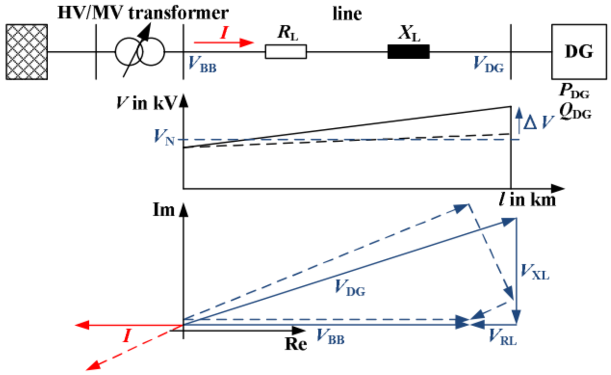

Figure 2: Schematic voltage profile in the MV grid in cases of decentralized power feed-in.

With the consumption of reactive power by the DG the voltage rise due to the feed-in of the active power can partly be compensated. The disadvantage of this method is the increase of the current and the resulting increase of the grid losses.

PRESENTLY USED VOLTAGE CONTROL CHARACTERISTICS BY LVN

The DSO has to specify the reactive power control mode and characteristic in the planning process of new generation plants [2]. In the MV grid of the LVN following control modes are specified:

Fixed Active Factors cosφ

In the LVN grid many DG operate with a fixed active factor $\cos\varphi = 1.0$, $\cos\varphi = 0.95_{\text{underexcited}}$ or with a $\cos\varphi = 0.95_{\text{overexcited}}$. Especially DG installed before or under the validation of the EEG 2009 were set up with $\cos\varphi = 1.0$, which is the most cost efficient control mode for the DG. Within 2009 the BDEW-guideline of 2008 [2] and a new revision of the EEG (2009) became effective which led to a change in the connection requirements of the LVN. Currently this control mode is mainly used for DG within industrial consumers or for non-fluctuation generation plants (e.g. biogas, combined heat and power plants CHP) with a minor effect on the grid voltage. Nevertheless a lot of DG units are still operating with this control mode.

Active Factor cos$\varphi(P)$

For presently installed PV-plants in the LVN grid a $\cos\varphi(P)$-control mode in the MV grid and also in the LV grid is used. Figure 3 shows the characteristic.

The active power of PV is very fluctuating. In less than 100 h per year, PV reach over 90 % of their rated power, but these hours appear mostly simultaneous over wide areas. Since, the grid voltage rises with the power feed-in into the grid, this active power generation is a good indicator for grid voltage, especially with higher amounts of installed power. The underexcited $\cos\varphi(P)$-characteristic (cp. figure 3) ensures the maximum voltage reduction at high generation ratios P/P_{Av} and a quite low reactive power in the most common operation states ($< 70\ \%\ P_{\text{Av}}$). PV-plants connected to the MV busbar have no noticeable effect on the grid voltage due to the voltage regulating tap changer at the HV/MV transformer. This plants are operated with the inversed overexcited $\cos\varphi(P)$-characteristic to compensate the reactive power consumption of the other plants distributed over the grid, instead.

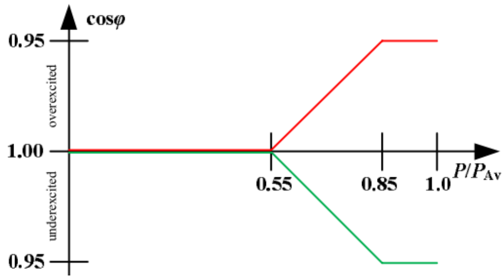

Figure 3: Under- and overexcited $\cos\varphi(P)$-control characteristic of LVN.

The main advantages of the $\cos\varphi(P)$-characteristic are that it is cheap and simple to setup and its high effect on the voltage. Due to the highly fluctuating PV and the very good correlation of the grid voltage to the power feed-in by PV into the LVN grid the additional reactive power losses are assumed to be low.

Reactive Power/Voltage Control $Q(V)$

When the DG generation characteristic has almost no correlation with the grid voltage the best control mode is a voltage dependent reactive power control $Q(V)$. In the LVN grid this is the case for biogas, CHP and wind generation. The $Q(V)$-control characteristic reacts more immediately on changes in the voltage value.

The $Q(V)$-characteristic reacts to voltage deviations of the reference voltage V_{ref} (20.0 kV) at the point of connection to the MV grid. If the voltage at the point of connection is higher than V_{ref}, the generation unit will decrease the voltage value by consuming reactive power. This is the underexcited operation area in the first quadrant of figure 4. The overexcited control mode in the third quadrant is used, if the voltage at the point of connection is lower than V_{ref}. This happens if high energy consumption meets low decentralized energy generation. In this operation area the remaining DG units should increase the voltage value with their reactive power capability. Figure 4 illustrates the standard LVN reactive power/voltage characteristic $Q(V)$.

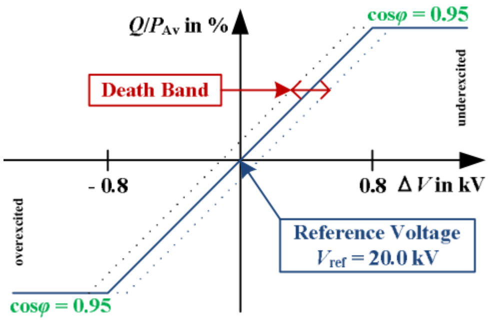

Figure 4: Standard LVN $Q(V)$-control characteristic

In both quadrants (one and three) the maximum reactive power is limited to 32.86 % of the active power feed-in P. This is equivalent to an active factor $\cos\varphi = 0.95$ which is the maximum requirement according to the German MV standard [2]. It is also possible to apply a death-band for the $Q(V)$-characteristic (cp. figure 4) to avoid potential reactive power/voltage oscillations caused by the dispersed independent voltage controllers in the DG.

If the slope of the characteristic line is not too steep [3], the reactive power control works very stable.

SIMULATIVE INVESTIGATION AND OPTIMIZATION

For the simulation the load flow calculation program PSS Sincal was used. It was not possible to implement additional control loops for $\cos\varphi(P)$- and $Q(V)$-characteristics directly in the load flow solving procedure. Therefore an embedded iterative script with the specific $\cos\varphi(P)$- and $Q(V)$-control characteristics for every DG was developed. These algorithms are written in the programming language VBA Script.

To check the correct function of the simulation and the basic assumptions for the DG a real MV-district has been modelled. At the most interesting points in the MV-district, measurements of voltage and feed-in power were conducted. With this data the simulation results were verified.

Development of $\cos\varphi(P)$ Algorithm

The algorithm for the underexcited $\cos\varphi(P)$-control characteristic calculates the ratio between the actual power feed-in P and the nominal active power P_{Av} for all DG in the MV grid. With the P/P_{Av} ratio a DG-specific $Q(P)$-characteristic is calculated. The actual point of active power P of the DG is given by a generation time characteristic for every type of generation (e.g. biogas, PV and wind characteristic). With P and the DG specific $Q(P)$-characteristic the reactive power value for the decentralized generation at a specific operation point is calculated and set in the load flow calculation. This procedure is used equivalent for all DG in every time step of the calculation process.

Development of $Q(V)$ Algorithm

The algorithm for the $Q(V)$-control characteristic is more complex because additional to the DG specific reactive power capability (limited by $\cos\varphi = 0.95$) the actual voltage value at the connection point is relevant for the set point of Q (cp. figure 4). The initial voltage is taken out of the first load flow calculation. But every change in the reactive power value affects the voltage in the grid. This change leads to a change of the Q-set point on every single DG and the voltage has to be calculated again. Therefore the reactive power is calculated in an iterative loop of load flow calculations until the changes in the reactive power are below the specified calculation tolerance. The whole iterative process of load flow calculation has to be done for all DG units for every calculated time step in a simulation setup.

MV-District Ellgau

The MV-district Ellgau was chosen for the simulative investigation of $\cos\varphi(P)$- and $Q(V)$-control characteristics at decentralized generation units. This MV-district is very rural and with only two MV feeders quite small. With that small district it was easier to verify the simulation process. Nevertheless the line length and feed-in power of these feeders are typical for rural MV-feeders of the LVN grid (cp. table 1). Additionally, one wind turbine with a $\cos\varphi(P)$-control mode is installed, so that the effects of the control modes could be compared not only by simulation but also by measurement.

Table 1: Basic data of the MV-district Ellgau.

Substation Ellgau		**Installed DG power in kW**	
HV/MV transf.; S in MVA	16.00	**Biogas**	1,245
Cable length in km	42.36	**Photovoltaic**	11,051
Overhead line length in km	23.29	**Wind**	2,400

Simulation Scenarios

The supply area of LVN as well as the MV-district Ellgau is characterized by a lot of decentralized PV generation (cp. figure 1 and table 1). Therefore sunny summer days with low consumption and a maximum power generation are the reference for high voltage situations. The summer day simulation shows the influence of the investigated control characteristics on the maximum voltage value in the MV grid. The opposite is the winter day with a high demand of electrical energy and a very low PV generation (< 10 % P/P_{Av} at cloudy weather). In the case of biomass generation with its average 5,700 full load hours, it is realistic to specify nominal power during the year [4]. The wind generators are at a power ratio of 90 % P/P_{Av} which is also realistic but mainly set up to show the difference between the different reactive power control modes under low voltage conditions. In both cases energy losses in the MV grid are compared.

SIMULATION RESULTS

For each simulation scenario - summer and winter workday - the simulation results show the development of the voltage and the losses in the MV grid (cp. figure 5 to 9). Simulations on weekend-days show similar tendencies and thus are not depicted separately.
In each chart the results for the three different reactive power control modes, pure active power feed-in (1), $\cos\varphi(P)$- (2) and $Q(V)$- (3) control characteristic are shown. The pure active power feed-in scenario is the reference scenario to show the effects of the investigated control modes. In the simulation, the voltage at the MV busbar in the substation was set to a fixed value of 100 % V_{N} (20 kV slack). So, the influence of a tap changer in the HV/MV transformer is neglected to illustrate the effects of the control modes, solely. For the active power mode of load and PV both measured load and generation profiles of the year 2013 were used.

Summer Workday

Figure 5 illustrates the influence of the control characteristics on the voltage level for the summer workday scenario (17th July 2013). Therefore, the node with the maximum voltage in the whole grid of every simulated time step was considered. In the diagram, the maximum voltage points in the grid are illustrated over the daytime. At every simulation step the node with the maximum voltage in the whole grid was considered. The voltage decrease due to the reactive power compared to the reference scenario without reactive power (1) is visible. The $\cos\varphi(P)$-control (2) has the most decreasing effect on the voltage which can be seen especially in times of high generation by PV at midday. The $Q(V)$-control (3) also decreases the voltage value at midday. It is less effective than the $\cos\varphi(P)$-mode (2) because the voltage rise in the MV grid of Ellgau is too low. To show the operation of the $Q(V)$-control at the saturation voltage of the $Q(V)$-characteristic at 106 % V_{N}, the busbar voltage was set to 104 % V_{N} (cp. figure 6). In this scenario the effect on the grid voltage is almost the same with both control modes (2, 3). Compared to the base scenario the reactive power of the DG reduces the voltage rise from + 2.8 % V_{N} (1) to + 2.0 % V_{N} (2, 3).

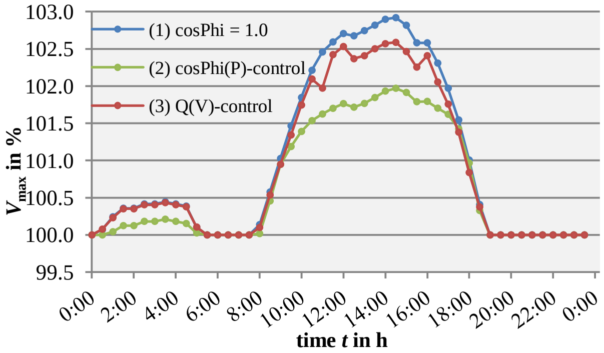

Figure 5: Maximum voltage in the grid on a summer workday with a MV busbar voltage of 100 % V_{N}.

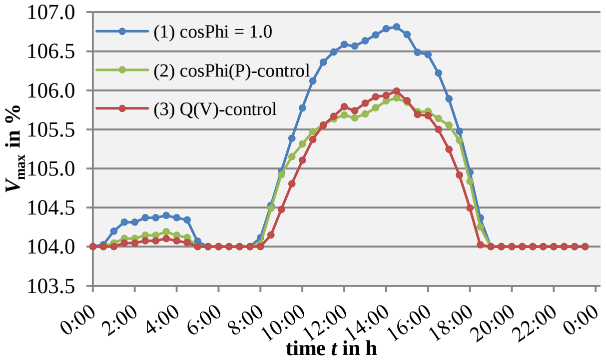

Figure 6: Maximum voltage in the grid on a summer workday with a MV busbar voltage of 104 % V_{N}.

In Figure 7 the losses in the MV grid according to the simulation scenario of figure 5 (100 % V_{N}) are shown. Caused by the high line-loading the grid losses reach their maximum at the maximum DG generation around midday (1, 2, 3). The $\cos\varphi(P)$-control (2) generates the highest losses in all situations due to the continuous reactive power consumption. This is, however, the downside of the advantageous effects on the grid voltage. The $Q(V)$-control mode (2) causes almost the same losses than the reference scenario (1) because of the low voltage rise compared to the reference voltage of the $Q(V)$-characteristic (cp. figure 4). If the decentralized generation rises, the $Q(V)$-mode also generates higher losses. But these grid losses are still lower than the losses with the $\cos\varphi(P)$-control mode.

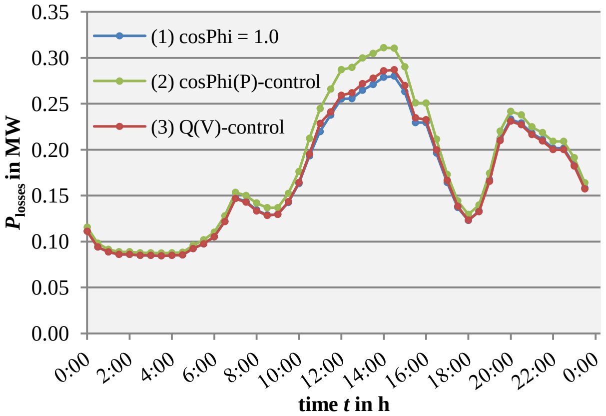

Figure 7: MV grid losses on a summer workday with a MV busbar voltage of 100 % V_{N}.

Winter Workday

The winter workday scenario was simulated with data gathered at 16th January 2013. Figure 8 represents the grid node with the minimum voltage value. Because of the higher energy demand and the low decentralized generation, the voltage in the grid is lower than the busbar voltage. Caused by the energy demand peak in the evening the minimum grid voltage is in the evening at 07:00 pm (cp. figure 8). In that situation there is no PV feed-in but wind and biomass units are still running.
When the underexcited $\cos\varphi(P)$-control (2) is used the remaining DG cause an additional voltage drop in this

situation because the cos$\varphi(P)$-control is not voltage sensitive and the feed-in power of biomass and wind is not correlated with the load flow situation in the typical MV grid of LVN. When the $Q(V)$-control is used the remaining DG increase the voltage value (3) by feeding-in reactive power (overexcited operation). The $Q(V)$-control mode and the pure active power feed-in scenario (1) lead to almost the same voltage levels in the night and early morning (lower energy demand) because the grid voltage is close to V_{ref} and the required reactive power of the DG is close to zero (cp. figure 4).

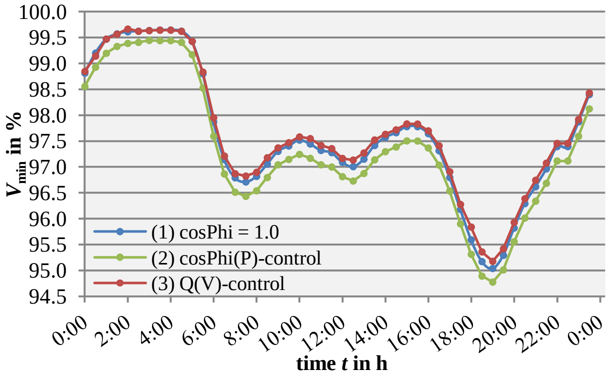

Figure 8: Minimum node voltage on a winter workday with a MV busbar voltage of 100 % V_N.

The grid losses for the winter workday scenario are shown in figure 9. The main part of the grid losses is caused by the active power flow and therefore proportional to the energy demand in this case.

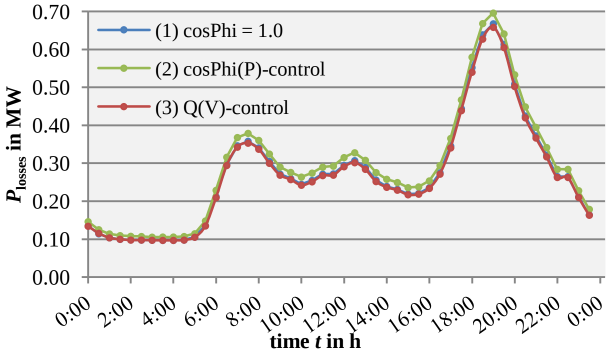

Figure 9: MV grid losses on a winter workday.

The additional grid losses caused by the reactive power control modes is the difference between the reference scenario without any reactive power from DG (1) and the control mode related curves (2, 3). The difference is smaller than in the summer workday (cp. figure 7) because the overall power of the DG and therefore their reactive power capability is much smaller. In winter the cos$\varphi(P)$-control characteristic also generates additional losses in all simulation points (2) because the remaining wind and biomass units are operating close to their nominal power and in maximum underexcited operation area according to figure 3. The $Q(V)$-control characteristic (3) slightly reduces the grid losses compared to the reference scenario (1). Especially in times of higher energy demand from morning to the early evening the low voltage causes an overexcited operation and therefore decentralized reactive power compensation takes place within the grid.

CONCLUSION

The simulative investigation of decentralized generation units (DG) with cos$\varphi(P)$- and $Q(V)$-control characteristic has shown that these control characteristics have an appreciable influence on the MV grid voltage. In times with high grid voltage and high feed-in from DG the cos$\varphi(P)$-mode has a strong decreasing effect. The disadvantages are fairly high losses and that the decreasing effect also reduces the voltage in high load/low generation scenarios. The $Q(V)$-mode has a lower influence on the maximum grid voltage but also lower losses over most of the operating time in the year. Especially in high load/low generation scenarios it increases the voltage and reduces losses. Due to domination of PV power plants (~75% of the installed Power) over other generation types and the fact that PV has very low operating hours, the cos$\varphi(P)$-mode for PV (high effect on the voltage, losses reduced due to low operating times) is acceptable. For other generation types (e.g. wind) and especially for generation types with a continuous operation and a lot of full load hours (e.g. biogas or CHP), the $Q(V)$-control mode is the best compromise of voltage limitation and grid losses. The disadvantage of the $Q(V)$-control mode in the field appliance are the more complex control structure and the fact that the currently used load flow calculation program do not support a simple model for the calculation.

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