DG-DEMONET SMART LV GRID – ROBUST CONTROL ARCHITECTURE TO INCREASE DG HOSTING CAPACITY

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ABSTRACT

This paper describes the impact of different voltage control strategies on low voltage grids with a high share of decentralised generation. These control strategies use the on-load-tap-change capability of new MV/LV-transformers as well as the capability of new PV inverters to control reactive power. The simulation results of the control strategies are compared with results obtained through long-term field tests in three Austrian LV grids. Furthermore the impact on voltage band allocation, grid losses, reactive power flow and number of tap-changes is discussed.

I. INTRODUCTION

Motivation

In future new demands on low voltage (LV) distribution networks will arise due to increased penetration of decentralised generation (DG) from renewable sources, but also due to new network participators like electric vehicles (EV) and increasing load caused by the transition of energy usage towards electrical energy e.g. usage of heat pumps for heating purposes.
Intelligent control approaches for LV grids based on an existing smart metering infrastructure that pursue the long-term objective of a "plug&automate" solution can be an alternative to grid reinforcement that is acceptable regarding investment, maintenance and operation costs.
The control algorithms investigated within the "DG DemoNet – Smart LV Grid" project are based on the control of the MV/LV-transformers on-load-tap-changer (OLTC) as well as on an area-wide Volt/Var (Q(U))- and Volt/Watt (P(U))-control of all PV inverters in the LV grid as well as on an P(U)-control of EV.

Related Work

The developed control stages that differ in required information and complexity are summarised in Section II and described in detail in [1] and [2]. These algorithms were tested in a flexible co-simulation environment that coordinates the simulation of the power grid with the simulation of the communication infrastructure allowing to model bandwidth and availability restrictions [3]. The architecture that enables a smooth transition from the controller operated in the simulation environment to the operation in field and minimises risks in deployment is described in [4]. The three LV grids "Eberstalzell", "Köstendorf", and "Littring" that were chosen for field trials are described in detail in [1] and [2].

II. CONTROL ALGORITHMS

The control algorithms developed within the project "DG DemoNet – Smart LV Grid" were designed to increase the hosting capacity of LV grids that is limited by voltage restrictions of the conventional power grid planning.
Three control "stages" were investigated. The higher the stage, the more information from the grid is necessary and the more complex the algorithm is, but also the impact of the controller on the voltage situation in the LV grid is more effective.

Stage 1 – local control: The most simple stage just performs a local control of the transformer's OLTC using busbar voltage while PV inverters are operated according to their default Q(U)- and P(U) control independently.
Stage 2 – distributed control: While inverters are operated the same way as stage 1, actual voltage measurements delivered from selected smart meters are used for distributed voltage control of the transformer's OLTC.
Stage 3 – coordinated control: The transformer is controlled the same way as stage 2. In addition the inverters' Q(U)-control can be adapted dynamically by the controller to reduce voltage spreading (the difference between the highest and the lowest voltage in the grid considering all three phases).

The P(U)-parameters of the inverters are set statically and not changed by the controller at any stage.
A detailed description of the control stages can be found in [1] and [2].

III. SIMULATION RESULTS

As described in [2] in detail, for each investigated grid simulations were performed for 18 typical days that represent all combinations of two seasons summer and winter, three weekdays Monday, Friday and Sunday, and three weather conditions sunny/good, partly cloudy/average and cloudy/bad. The underlying power

profiles for these 18 days are composed of measured consumer- and generation profiles with a time resolution of one minute. Voltage trends of a selection of these typical days where published in [1].
The following results are based on an extrapolation of these typical days to one year.

Effectiveness of the control stages

Although the implementation of the control stages in LV grids can lead to a rise in hosting capacity, simulations (as well as field tests) were performed with the same hosting capacity for all control stages. Therefore the impact of the different control stages on the grids was measured by the voltage band allocation that decreased with increasing control stage. Control stages that are benchmarked by voltage band allocation and not by hosting capacity need different control parameters for the inverters' reactive power characteristic curve as well as for the OLTC-controller's voltage limits to produce convenient results. In general, a significant dependence of the simulation results on several simulation parameters was observed. Figure 2 and Figure 3 show selected simulation results that are compared to field test results and discussed in section IV.

Effects of control stages on reactive power flows

Figure 1 shows the relevant parts of the duration curves of the reactive power flow over the transformer for all three investigated grids. The simulations were performed in a way that reactive power was used sparingly. Therefore the duration curves of stage 1 (yellow) und stage 2 (blue) are near the duration curves of the reference scenario (green). Of course, lowering the starting point for the inverters' reactive power contribution would force inverters to consume reactive power and result in larger voltage band savings for control stage 1 and 2. Stage 3 was configured to use as much reactive power as needed to keep the spreading of grid voltages small. As shown in Figure 1, this leads to a doubling of the peak reactive power flow in the investigated grids.

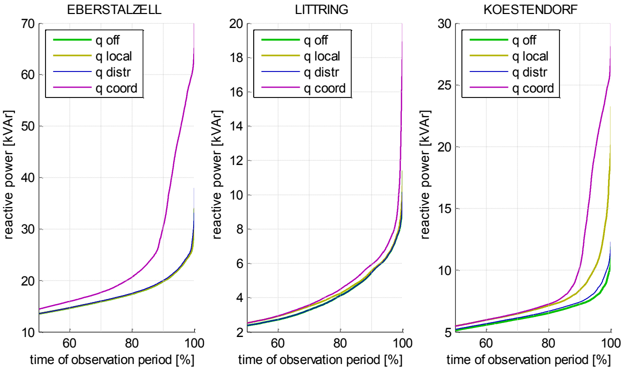

Figure 1 Simulation results: Upper half of the duration curve of reactive power flow over the transformer in the three investigated grids (transformers' rating: 630/250 /250 kVA respectively)

A cos(phi(P,0.9))-characteristic requires reactive power at 48.4% of active power at maximum level resulting in 0.46kVar/kWp. The simulation for voltage control demonstrates much lower reactive power requirements in the range from 0.13 kVar/kWp up to 0.25 kVar/kWp.

Even if the amount of controllable reactive power is rather limited in these grids, a more thorough study about the large scale impact of such controls at high voltage grid would be needed before a large scale deployment.

Effects on number of tap changes

The number of necessary tap changes also depends on the interplay between the OLTC control at the secondary substation and the inverters Q(U) control, especially for the distributed voltage control which is reacting on voltages measured in the LV feeders. When the starting point of the inverters' reactive power droop control is below the voltage the OLTC controller performs a down-tapping, it is possible to save tap-changes because of the effect reactive power control has on the voltages. However, the most promising technology (vacuum switching) does not need any maintenance, therefore the number of switching operations is not as such a limitation and it is not meaningful to use Q(U) to avoid tap-changes.
Furthermore the number of tap changes also strongly depends on the variation of the MV grids voltage, but also on the MV/LV-OLTC's and the HV/MV-OLTC's tap-size as well as on the LV grid's power flows for stage 2. The investigated grids are situated within the half length of the MV-feeder in the primary substation (HV/MV), so MV voltage variations are rather limited. Due to constructional reasons of the transformers (limited number of windings) rather high switching taps at the low voltage side were given. As a result, very few tap changes occurred in stage 1.
Table 1 shows the simulation results for all three grids. As mentioned above, the extensive usage of reactive power from inverter's Q(U) control in stage 3 can save tap-changes compared to stage 2.

Stage	Eberstalzell	Köstendorf	Littring
1	0.6	0.6	1.4
2	4.1	3.1	3.8
3	3.5	1.9	2.9

Table 1 Average number of tap-changes per day

Effects of the control strategies on grid losses

In general grid losses increase with increasing grid load, and the integration of DG tends to decrease grid losses as long as the generation is locally consumed over a significant period of time. When reverse power flow occurs, losses will increase again with increasing installed DG power.
The simulations show that in the investigated grids, the daily mean values of grid losses vary around 20% of the

average daily mean grid losses depending on the load situation (working day or weekend). In winter, grid losses are two fold higher as in summer due to the increased load on the one hand and the decreased PV infeed on the other hand. In all three grids, grid losses increase with increasing PV infeed in summer (around 25% between sunny and cloudy days due to reverse power flow), and decrease in winter (around 10% between sunny and cloudy days).

The investigated control stages influence grid losses via the usage of reactive power from PV-inverter's Q(U) control and via the overall voltage level set by the OLTC. The latter influences grid losses due to the voltage dependency of the loads and is negligible when loads are modelled as P-Q-constant. The former significantly depends on the interplay between the OLTC controller and the Q(U) controllers, especially for stage 2 and 3. When the controller is configured in a way to perform a down-tapping (if possible without violating the lower limit) before the PV-inverters' reactive power contribution starts, the inverters' reactive power flow in the grid will be minimised as much as possible. Simulations showed that average grid losses of a whole day increase with extensive reactive power contribution on sunny summer days up to 15%, but considering the whole year, grid losses do not increase significantly. The worst result obtained from simulations was a relative increase of +4% for stage 3 compared to stage 0.

IV. FIELD TRIALS

In the last phase of the project "DG DemoNet – Smart LV Grid" the developed control strategies were implemented and operated in three Austrian LV grids over more than a year.

Field test operation of the controller

The controller was operated directly at the secondary substation. The environment of the controller offers a web-interface for configuration, grid- and controller-status and logging. This interface was remotely accessible by the DSO so that the integration into the grid operation management was not necessary.

Evaluation Approach

The rise in hosting capacity in LV grids is related to the gain in available voltage band for the integration of PV or EV. Therefore it is expected that higher control stages need less voltage band than lower control stages and the uncontrolled conventional grid operation.

While in simulations exactly the same power profiles can be used for the simulation of all control stages making the simulation results easily comparable, in the field tests the load-situations are not reproducible. Therefore the results for the gain of voltage band for each control stage have to be regarded in respect to this uncertainty. The performance of voltage control concepts can be compared by either evaluating over a very long timespan or evaluating during a short period of time of less than one hour during a smooth grid situation where the power flow situation does not change significantly. Of course, short term tests within one hour cannot give a comprehensive statement about long term performance, but it gives an impression about the behaviour of the control strategies and their potential to improve grid voltages.

To obtain meaningful results, the impact of the control stages on the grid voltages was observed during the evaluation phase over several months. A similar approach as for the predecessor project "DG DemoNet Validation" was chosen where voltage control concepts for MV grids were compared [5]: The different control stages were automatically switched in a daily cycle at midnight during the whole evaluation phase.

Since power flow fluctuation in LV grids strongly depends on season, weekday and weather, the voltage values that are recorded and the situations causing them during the different active control stages have to correspond with each other to be comparable. By daily switching control stages over a time period of several months, the likelihood that load and infeed situations occur equally in every investigated stage is maximised. Nevertheless the extreme situations (e.g. load peaks) will not occur equally for each investigated stage, which would make an evaluation time period of at least one to three years necessary. Since such long time periods were not possible within the scope of the project, those cases have still to be covered by simulations being aware that appropriate load models are typically not available and the worst case occurs at low probability. Table 2 shows the different control strategies that where switched in a daily cycle.

Stage	Name	OLTC	PV Q(U)
0	conventional grid control	off	off
1	local control	local voltage control	static
2	distributed	distributed voltage control	static
3	coordinated	distributed voltage control	dynamic

Table 2 Control stages operated in evaluation phase

Field test measurements

In order to be able to analyse the LV grids in detail and to answer questions going beyond the scope of the project, an extensive monitoring infrastructure was installed and operated.

To gain precise and reliable measurement records during the field tests, 28 power quality measurement devices (with time synchronisation) that record grid voltages according to EN50160 in a 10-min-average-interval were installed in two of the three grids. Furthermore in these two grids the metering system enabled the recording of four-quadrant power profiles within a 15-min-average

interval at participating customers. Dedicated meters for each installed inverter gave insights on the behaviour of each single inverter within a 15min time resolution.
In the third grid, every PV inverter delivered active and reactive power as well as the PV inverter's terminal voltage within a 5min time resolution. Moreover, rough information about the power flow of the buildings equipped with PV installation where available within a 5min time resolution.
In all three grids the voltage controller was supplied with actual voltage measurements from selected smart meters by EGDA (Express Grid Data Access – an addition to the AMIS CX1 power line communication protocol). With EGDA it was possible to transfer moving-5min-average-values of selected smart meter voltages over PLC (power line communication) with a delay time of around one second per data point.
Furthermore, in one grid the PSSA (Power SnapShot Analysis - an analysing technique for LV grids based on smart metering infrastructure [6]) was also used to get detailed insights of the control behaviour of PV inverters operating with Q(U)-control.
For comparison of voltage band usage, the 10-min-average values from the power quality measurement devices were taken where available. Otherwise, the 10-min-average values were reconstructed from the smart meter's moving 5-min-average values received by EGDA.

Selected preliminary field test results

Voltage band usage: It is clear that an evaluation period of several months cannot cover all peak-load situations that typically occur within the grid. When increasing the evaluation time period, new peak-load situations can lead to an increase in voltage band usage. Therefore the voltage band usage of the different stages shown in Figure 2 and Figure 3 is only the lower limit of the real voltage band usage.
The comparison with the simulation results show, that voltage band usage in simulation was up to 20% higher than in field test. The main reasons for this are that the simultaneity factor of the loads was assumed too high on the one hand, and that field test phase was comparably short on the other hand.
Furthermore, field tests showed that the busbar voltage variations were smaller than the controller's deadband for local voltage control (because tap size was too large). Thus in stage 1 the transformer did not perform any tap-changes. Therefore stage 1 was renamed to Q(U), because the transformer acted like in reference scenario, and the only difference was the inverter's Q(U) control.
Figure 4 and Figure 5 show a reason why the savings in voltage band shown in Figure 2 and Figure 3 are limited: Distributed voltage control of stage 2 can save voltage band if it performs a down-tapping in times of high DG infeed resulting in high grid voltages. But this only makes sense if in times of high grid voltages the lowest grid voltages are also rising so that a voltage band reserve evolves between the lowest voltage in the grid and the controllers lower voltage limit – otherwise a down-tapping to avoid upper-limit-violation would lead to an under-voltage situation. Figure 4 and Figure 5 show that in times of high maximal voltage rises (upper part of the blue line), the maximal voltage drop only decreases slightly (green line that represents the max. voltage drop sorted accoring to the order of the max. voltage rise).

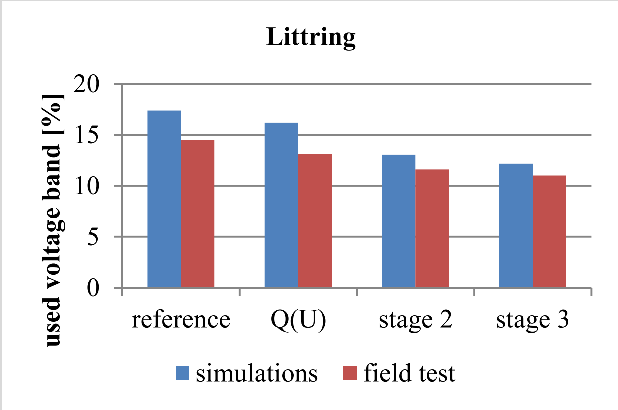

Figure 2 Voltage band usage in Littring

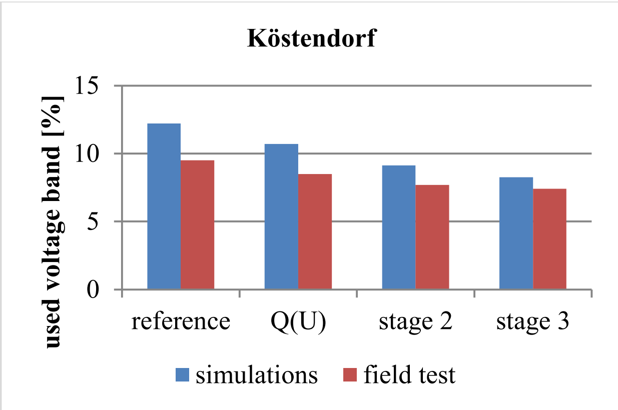

Figure 3 Voltage band usage in Köstendorf

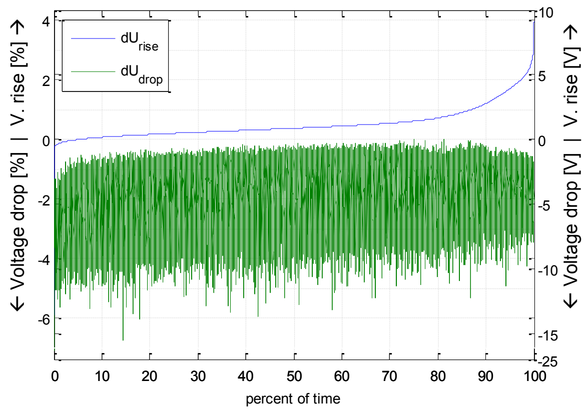

Figure 4 Duration curves of voltage rise and drop in releation to the transformer's busbar voltage (sorted according to voltage rise) in Köstendorf over one year (all operated control stages included)

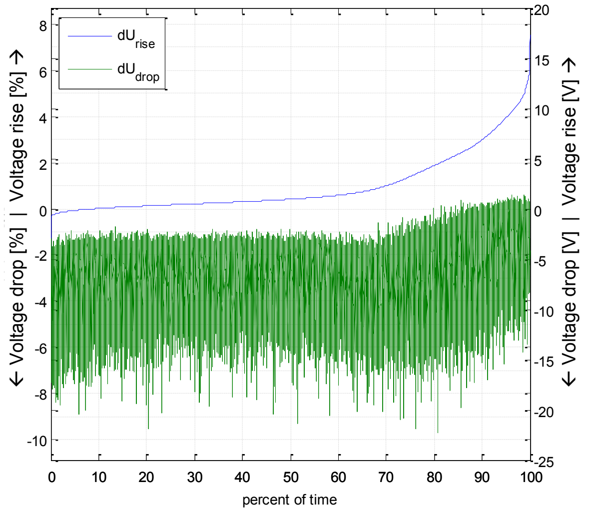

Figure 5 Duration curves of voltage rise and voltage drop in releation to the transformer's busbar voltage (sorted according to voltage rise) in Littring over one year (all operated control stages included)

Tap change frequency: Figure 6 shows the amount of days with zero to five tap-changes for Littring. Even in stage 2 (blue), in 40% of the days no tap-changes occured. Stage 2 often uses more tap changes than stage 3 (purple), which confirmes the results of the simulations.

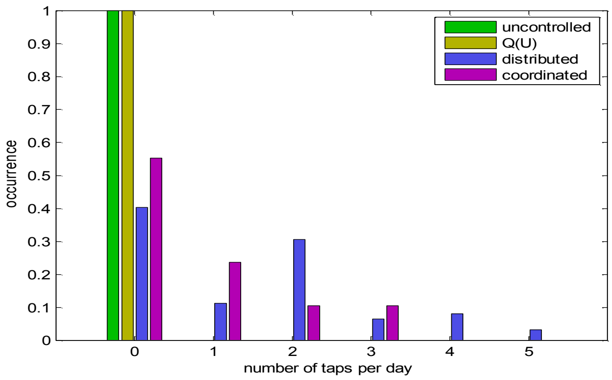

Figure 6 Occurrence of number of tap changes per day in Littring

VI. CONCLUSION AND OUTLOOK

Simulations as well as field tests are demonstrating the general feasibility of the developed "DG DemoNet Smart LV grid" solutions. As predicted, the higher the control stage, the less voltage band was needed by the solution. But it must be stressed that the impact of the solutions on voltage band and reactive power flow significantly depends on the configuration parameters of the controllers involved. Using sensible configuration parameters, effects on grid losses can be neglected. Nevertheless further analysis about the effects of a significant increase of reactive power generated in LV grids on superior grid levels is needed.

The technical as well as the economic benefits of the developed solutions depend on the individual grid. Since only three grids are currently investigated, it may be difficult to evaluate the benefits of the developed solutions as well as the potential for future grids. These topics are currently under investigation, results will be published in the near future.

For network planning, not only the relative quantity of voltage band usage is relevant, but also the location of the grid voltages within the voltage band given by EN 50160. Currently intelligent planning approaches are investigated that help to get a more realistic assessment of grid voltages than with conventional power grid planning. It is expected that just by applying more flexible planning approaches, monitoring of real voltage levels and optimising the grid configuration with tools like power snapshot analysis, the maximal hosting capacity of LV grids can be enabled.

ACKNOWLEDGMENTS

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