EFFECTIVITY OF ACTIVE VOLTAGE CONTROL CONCEPTS IN DISTRIBUTION GRIDS

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ABSTRACT

This paper deals with comparing the effectivity of different active voltage control strategies like cosφ(P), Q(V), on load tap changer(OLTC)-transformers, line voltage regulators (LVR) or STATCOMs for the integration of decentralized energy resources (DER) in distribution grids. All examinations are based on a combined symmetrical three-phase MV/LV-distribution grid simulation model for rural areas. Probabilistic and static load flow calculations take respect to different tasks of supply and paths of DER-penetration. A separated planning of MV and LV grid is considered as well as a common network planning for MV and LV. Results are hosting capacities and efforts for network extension.

INTRODUCTION

The grid integration of renewable decentralised energy resources (DER) is linked to several challenges for distribution system operators (DSO). In most cases, the grid capacity is not limited due to congestion of grid devices but by violating allowed voltage limits [1]. For that reason, according to "BDEW guideline generating plants in the MV-grid" [2] and VDE AR-N 4105 [3], distributed generators have to be equipped with voltage control mechanisms like cosφ(P) or Q(V). Next to conventional grid reinforcement, DSOs have the possibility to install dedicated voltage control devices like OLTC-transformers, line voltage regulators (LVR) or STATCOMs. The challenge is to choose a technical and economical sustainable voltage control strategy.

METHODOLOGY

Task of supply

The grid structure shown in Figure 1is modelled as a rural MV-feeder with 33 subordinated LV grids [5] and a total number of 2420 nodes[4]. The plant's power range is set by the network level (see Table 1) of the point of common coupling (PCC).

Table 1: typical DER power in different network levels

network level	5 (MV)	6 (MV/LV)	7 (LV)
DER type	Wind,PV	PV	PV
Power in kW_p	200-5500	30-200	1-30

The exact rated active power is obtained from the distribution function shown in Figure 2. In case of reactive power control, all generators are assumed as oversized (apparent power greater than P_{DC}) to provide additional reactive power without reducing the feed in of installed active power. The minimum cosφ can either be set to 0.9 or to 0.95 [3].

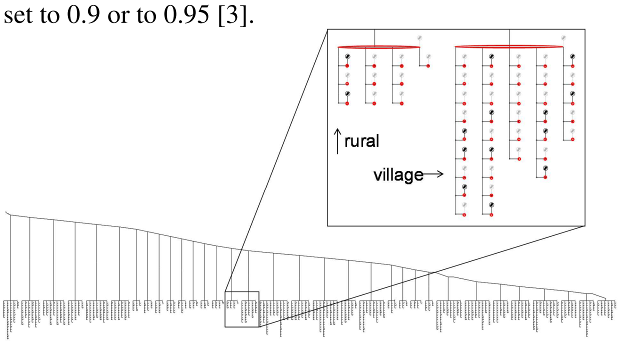

Figure 1: Network structure of the rural grid model

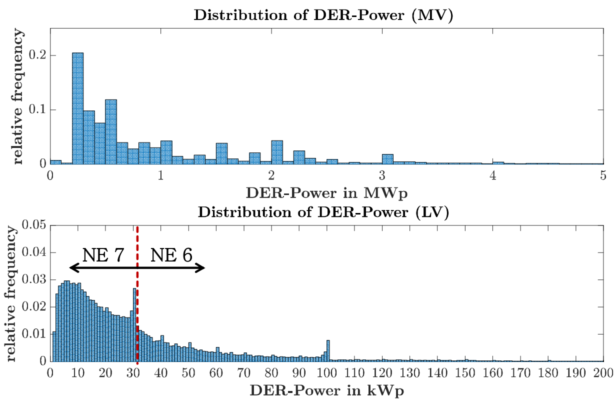

Figure 2: Distribution function of installed DER-Power

Simulation sequence

As described in [4], decentral power plants from the distribution function (Figure 2) were arbitrarily connected to PCCs. For evaluation of grid connection, loads are neglected. 1000 different grid configurations were considered in order to take the influence of varying power plant positions into account.

Parameter definition

Six voltage control scenarios are defined and investigated. In this approach, parameters are unified for all devices in the entire grid area.

cosφ(P)

All DER are equipped with voltage control functionality. Evaluating the grid connection of each power plant is done using the maximum real power and the minimum cosφ according to VDE AR-N 4105 appendix E [3].

Q(V)

All DER are equipped with voltage control functionality. For connection evaluation, maximum real power will be fed in. Since provided reactive power will be dependent on the nodal voltage at the PCC, there can be set no fixed reactive power. The assumed characteristic from [10] is shown in Figure 3.

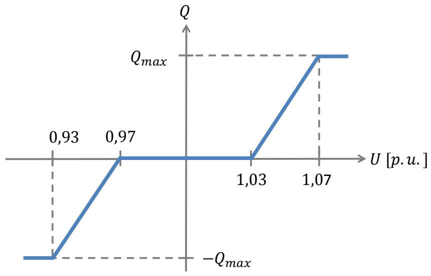

Figure 3: Q(V) characteristic [10]

OLTC-transformers

The tap ratio of all MV/LV-transformers can be changed to decouple the MV and the LV grid. The very common and simple control strategy is used here: a defined voltage setpoint of 1.0 p.u. is kept at LV busbar in the transformer station by changing the tap ratio. For the following consideration, the change ratio can be varied stepless.

LVR

In this scenario, voltage regulators are installed in the LV grid in case of violating voltage limits (formally 3% criterion). The maximum power rating of the devices is adapted to the line capacity (typical 200 kVA). Due to recommendations in [6], the LVR is placed after 33% of total length of the feeder. Voltage setpoints are chosen analogous to the scenario OLTC-transformer. The amount of installable LVR is limited to two devices per LV-grid.

STATCOM

In case of voltage violations, a centralized Q(V)-control is installed in the LV grid at the end of the concerning feeder [7]. The characteristic is equal to Figure 3. The rated power (Q_{max}) of the STATCOMs is set to 100 kVAr (corresponding to 50% of typical line capacity). In order to avoid additional congestions, a maximum of two devices is used in the same LV-grid.

Limits

As mentioned in [4], there are several limits that have to be taken into account when planning distribution grids.

Thermal overloading

In all cases, thermal congestions have to be avoided by reinforcement of the devices (e.g. lines and transformers). For lines, voltage range deviations will occur long before thermal limits are reached [8]. Congestions of MV/LV-transformers are likely to happen more often, mainly in LV grids fed by small transformers (< 400 kVA).

Voltage limits

For designing the grid, two planning criteria are defined as suggested in [4]: **conventional network planning** and **integral network planning**.

<u>Conventional network planning</u>:

The “**2%-criterion**” and the “**3%-criterion**” define a maximum voltage rise of $\Delta v_{DER,MV}$ =2% caused by decentral power plants connected to MV [2] and $\Delta v_{DER,LV}$=3% caused by such connected to the LV [3] grid. This means, that there is a **fix partitioning of the voltage band** without the need of a coherent MV/LV grid. These rules are meant as a simplified planning tool for DSOs to do a voltage level decoupled grid planning. By sticking to the proposed values, it is assumed, that the absolute voltage limit of V_N±10% according to EN 50160 [1] will be fulfilled automatically without considering the voltage rise in the MV, caused by LV-DER. In case of using OLTC-transformers, the 2% and 3% criterion are neglected [3], otherwise there would be no benefit when using OLTCs. In case of using Q(V), the 2 %- and the 3 %-criterion have to be checked carefully: according to the used characteristic in Figure 3, providing reactive power starts at a nodal voltage of 1.03 pu. Therefore the 3 %-criterion could be violated, even before voltage control starts. Nevertheless, it could be far from exceeding the maximum allowed voltage of 1.1 pu. In this case Q(V) would be useless. Unfortunately the codes don’t propose a proceeding for testing the effectivity of Q(V) control in the grid.

As a solution, this paper suggests to consider also the **voltage preload caused by the other grids** (that pends to violate the global voltage limit) by adapting the slack bus voltage during testing the 2 % and 3 %-criterion to:

$$\begin{aligned} V_{\text{slack,dV}} &= V_{\text{max, 50160}} - \Delta V_{\text{tol}} - \Delta V_{\text{ARN4105}} \\ &= (1.1 - 0.02 - 0.03)pu = 1.05\,pu \end{aligned} \tag{1}$$

Investigations in [9] also validate this assumption.

<u>Integral network planning</u>:

It is just required to keep the voltage limit of V_N±10% at all PCCs according to EN 50160 [1]. There is **no fixed voltage band partitioning** between MV and LV. This requires a holistic model of all rigidly coupled parts of the grid. In the following simulations, the maximum value of $V_{max,\ 50160}$ was reduced to $V_{max,\ global}$=1.08 pu to keep a safety margin for inaccuracies due to the HV/MV-OLTC and asymmetries between the phase voltages. The voltage at the beginning of the MV feeder is assumed as V_{slack}=1.0 pu.

Network extension mechanism

In cases of violating limits, the existing grid structure will be reinforced. The proceeding depends on the voltage level and is done as described in [4] and [10].

MV network

Violations at MV-nodes are fixed by installing new parallel lines stepwise beginning at the substation and moving to the violated node until limits are fulfilled as depicted in Figure 4. To avoid a feedback between different LV grids, a maximum voltage rise up to 1.05 pu has to be kept to provide a voltage band of at least 3% for LV grids. The standard cable type NA2XS2Y 3x1x185mm² is used.

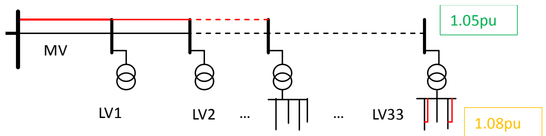

Figure 4: MV-network extension mechanism

LV-network

According to [10] and Figure 5, a new LV feeder is created by splitting up the old LV-feeder of the violated node after 2/3 of feeder length. The standard cable type NAYY4x150mm² is used for this.

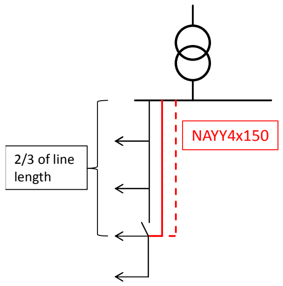

Figure 5: LV-network extension mechanism

RESULTS FOR HOSTING CAPACITY

Hosting capacity is defined as the amount of installable DER- peak power by meeting all voltage and congestion limits without major changes of the grid (except the exchange of MV/LV-transformers). Results are displayed in Figure 6. Determined hosting capacities are illustrated for each voltage control strategy in boxplots for conventional (black boxes) and integral network planning (blue boxes). The middle line of the box represents the median (q_{50}), left and right line mark 5% (q_5) and 95% (q_{95}) quantile. Whiskers show minimum and maximum values.

Conventional network planning

The basic scenario without using any voltage control shows the smallest amount of installable DER-power (q_{50}=2.2 MWp). In comparison, OLTC-MV/LV-transformers show the best performance (increase of 480 %). Decentral reactive power control cosφ(P) and Q(V) offer the second best effectivity by increasing the median hosting capacity about 45 %. Changing the minimum cosφ from 0.9 to 0.95 would lead to a slight decrease (cos φ(P): 2 %, Q(V): 5 %) of effectivity. Hence Q(V) offers nearly the same results as cosφ(P). Similar results can be found in [10] and [11]. Voltage control by LVR offers the lowest efficiency with about 20 % median increase of hosting capacity. Centralized reactive power control by LV-STATCOMs shows less efficiency (q_{50} increase rate: 25%) compared to distributed Q(V).

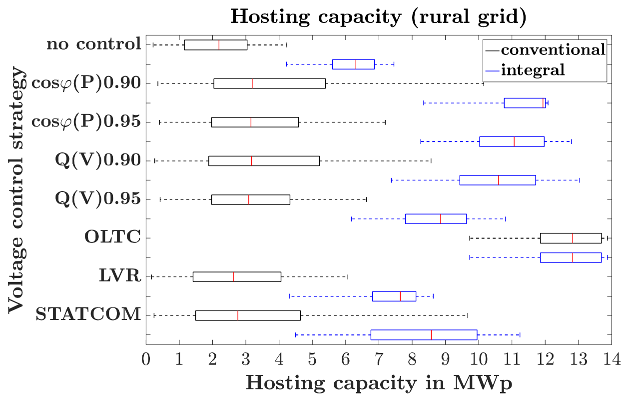

Figure 6: Effectivity of voltage control strategies using different planning criteria

Integral network planning

The blue boxes in Figure 6 show the results for applying a combined MV/LV-network planning. In the basic scenario, hosting capacity is increased significantly (185 % more than in case of a conventional planning are corresponding to the increase of the available voltage band from 3% to 8%). The OLTC-transformer performs as most powerful tool by doubling the hosting capacity. Using the entire voltage band illustrates the differences between the voltage control concepts. cosφ(P) remains the most effective mechanism with an increase rate of 90 %. Reducing the reactive power ($\cos\varphi_{min}$=0.95) goes with a lower increase rate of 75 %. Q(V) can offer an increase rate of 69 %. Raising the $\cos\varphi_{min}$ to 0.95 results in lowering the increase factor to 40 %. Again, the scenario "LVR" offers the lowest effectivity (about 20 % higher hosting capacity than in the basic scenario). It can be seen that integral network planning offers additional potential as mentioned in [4] and [10] but has no influence on the general behaviour of the considered control strategies.

RESULTS FOR GRID EXTENSION

The results for grid extension are calculated for conventional and integral network planning and shown in Figure 7 - Figure 10. For each DER-penetration rate, the necessary extension is given as line length in km and determined for MV and LV separately.

Conventional network planning

MV network extension

At first sight, there are only small differences between all scenarios. The median line length shows to be around 10 km, corresponding to the half of the entire MV-feeder length. The scenario without voltage control and the scenario LVR behave equally: the median efforts are rising from 4 km to 19 km. OLTC can prevent most incidents in the MV feeder. All reactive power control strategies can reduce MV grid extension but don't show the same influence compared to LV-grids. Reinforcement is triggered by violating the 2%-criterion and violation of 1.05 pu in the MV-grid. Effectivity of reactive power is reduced by the HV/MV-transformer, because the OLTC would control the voltage to 1.0 pu and thus eliminates the voltage drop of the transformers inductance. [12].

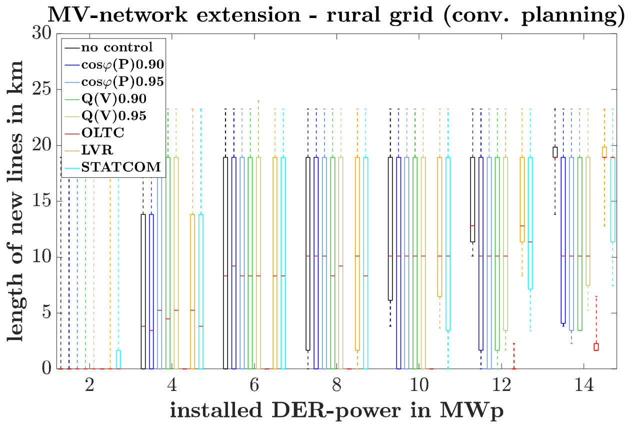

Figure 7: MV-network extension (conv. planning)

LV-network extension

Considering the reinforcement of the LV grid in Figure 8, it appears that the first scenario without any voltage control (black box) requires by far the most interventions. The sequence looks almost to be exponential. Full penetration of 14 MW_p will lead to at least 95 km of additional LV-lines (caused by violating the 3%-criterion). On the contrary, the scenario "OLTC" requires no reinforcement of the LV-grid at all. The scenarios cosφ(P) (blue/pale blue) and Q(V) (green/pale green) require significantly less interventions than the basic scenario. At high DER-penetration rates, cosφ(P) shows a slightly higher efficiency, than Q(V).

The LVR (orange) needs a of lot of interactions, while LV-STATCOMs show a effectivity between Q(V) 0.9 and cosφ(P) 0.95. Both scenarios are limited by the maximum allowed number of devices.

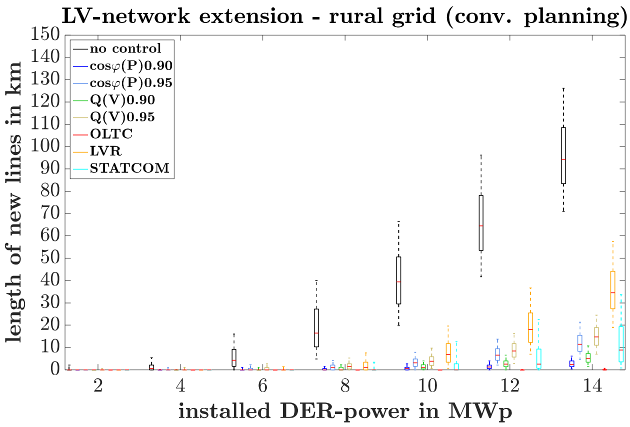

Figure 8: LV-network extension (conv. planning)

Integral network planning

MV network extension

As depicted in Figure 9 and according to the results for hosting capacity, there is no need for new MV lines at DER-penetration-rates below 8 MW_p The scenario "no control" and "LVR" behave equal: the median efforts are rising from 4 km to 19 km. OLTC-transformers can also prevent most of the incidents in the MV feeder because the 1.05 pu-MV-limit can be neglected (no LV-reserve has to be kept). Reactive power control strategies reduce MV grid extension in a better way compared to conventional planning because reinforcement is mainly triggered by the influence of LV-DER. They tend to violate the global voltage limit of 1.08 pu and hence trigger MV grid extension for keeping the voltage at the MV nodes at 1.05 pu.

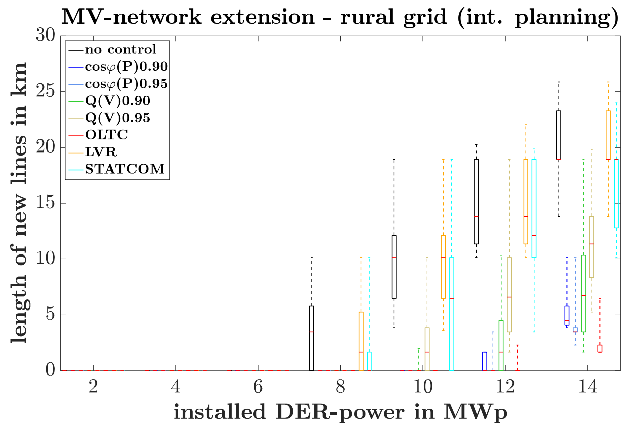

Figure 9: MV-network extension (int. planning)

LV-network extension

Compared to a conventional planning, the first scenario in Figure 10 without any voltage control requires just one fifth of the necessary efforts from Figure 8. The required line length now rises with a significantly smaller pitch. All efforts are now in the range up to 20 km. The behaviour of the other scenarios does not show a significant difference when comparing integral and conventional network planning.

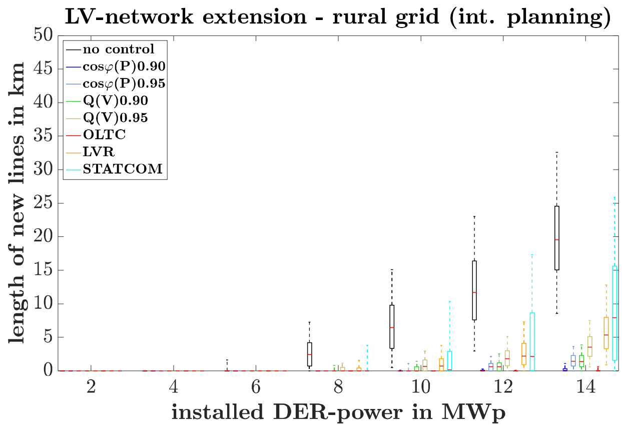

Figure 10: LV-network extension (int. planning)

SUMMARY & CONCLUSION

This paper assesses the effectivity and sustainability of voltage control strategies in distribution grids by determining a technical hosting capacity as well as penetration dependent efforts for grid extension. By using a combined MV/LV grid simulation model, the coupling of the voltage levels is taken into account and different network planning criteria are considered.

It was demonstrated, that OLTC-MV/LV-transformers show the best effectivity. This solution should be considered if high penetration rates are expected in the network area. The most common voltage control cosφ(P) shows a very good performance - nearly reached by Q(V), that shows further advantages with regard to the efficiency [11]. In both cases it is recommendable to allow a lower value for cosφ of 0.9. Both cosφ(P) and Q(V) could be used for medium penetration rates. Due to the poor effectivity, LVRs and LV-STATCOMs are not suitable for a LV-grid comprehensive voltage control and should be considered for individual short term solutions. It was also proven, that using a combined MV/LV-planning offers a better utilization of the grid capacity and saves a lot of effort in combination with active voltage control strategies. The methodology was developed during the German-government-funded research project "U-Control".

Gefördert durch:
Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages

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