APPLIED APPROACH FOR REACTIVE POWER CONTROL WITH MEDIUM VOLTAGE DISTRIBUTED UNITS

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ABSTRACT

Decentralized generators in modern distribution grids are supposed to take part in providing ancillary services e.g. reactive power control. This paper presents an approach to parameterize distributed Q(U)-controllers by evaluating the optimal centralized reactive power controller. Applying this method to a medium voltage grid raises grid capacity by around 60%.

INTRODUCTION

The more renewable sources contribute to energy systems, the more generation is shifted to distribution grids. Now, ancillary services also need to be provided by smaller and distributed plants. To realize this, many grid codes (e.g. [1]) enable distributed generators, like PV-plants, to do various control strategies, such as reactive power control. However, the question now is: How should these controllers be parameterized in an existing grid or how do parameters change if grid structure changes, e.g. connecting a new plant?

Recently, research projects focused on reactive power control strategies for electrical distribution grids that are exposed to a large amount of renewable energies [3], [4], [5], [6]. This paper contributes to current literature by suggesting a method to parameterize distributed reactive controllers that depend on the local voltage. This approach is based on a centralized controller that knows complete grid data and can optimally control the grid. Optimal in this context means keeping voltages in the defined limits and to minimize reactive power at the same time. This avoids overloading grid components. Parameters for the distributed controllers are derived based on these results. In the following sections, methods will be derived and presented with the medium voltage feeder showcase.

MV-FEEDER SHOWCASE

The medium voltage feeder presented in Figure 1 is used to illustrate the methods derived for defining distributed controllers for reactive power control. This feeder, with a nominal voltage of 20 kV, is coupled with a transformer, $S_N = 25$ MVA, to the high voltage grid. The cables of type NA2XS2Y1x070 connect 6 PV-plants (PV1, PV2, PV3, PV4, PV5, PV6). Nominal powers of the plants and distances in the grid can be seen in Table 1.

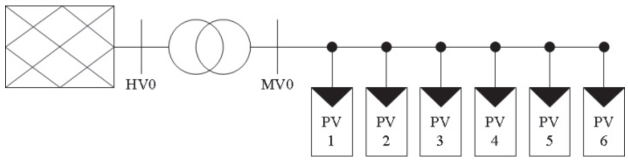

Figure 1: MV-grid structure used for the controller analysis connects 6 PV-plants.

Table 1: shows distances in the grid and the nominal active power of the productions units.

	PV1	PV2	PV3	PV4	PV5	PV6
Distance to previous node in km	0.5	0.5	0.5	1.0	2.5	1.0
Nominal Power in MW	.4	.4	.5	1.3	3.1	1.3

CENTRALIZED OPTIMAL Q-CONTROLLER

A centralized optimal Q-controller is used in the previous defined grid to gain information about the potential of reactive power control (Q-control). This information can be used for the parameterization of a decentralized controller.

Definition

Optimality of control is assured by connecting and processing all relevant grid data. In a real system this would require a high-speed communication infrastructure as well as high real-time computing power, which is expensive. Relevant measurements are voltages at the nodes, the active and reactive power at the points of connection. To guarantee ideal usage of reactive power, it is necessary to know the impact of reactive power feed-in at one point on the voltages of all nodes.

The dependency of reactive power feed-in at each node to the voltage on each grid node can be obtained from the Newton-Raphson method as proposed in [3]. To calculate load flows, the Jacobian matrix according to [2] is first set up. With the Jacobian the relation between powers and voltages is described by:

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} \Delta \vartheta \\ \Delta U \end{pmatrix} \quad (1)$$

The inverse of the Jacobian depicts the required sensitivity matrix in order to calculate the effects of reactive power feed-in. The southeast corner, dU/dQ, represents the desired relation between Q and U.

$$\begin{pmatrix}\Delta\vartheta \\ \Delta U\end{pmatrix} = \begin{pmatrix}\frac{d\vartheta}{dP} & \frac{d\vartheta}{dQ} \\ \frac{dU}{dP} & \frac{dU}{dQ}\end{pmatrix}\begin{pmatrix}\Delta P \\ \Delta Q\end{pmatrix} \quad (2)$$

The controller measures all nodal voltages to control the voltage. If one voltage moves beyond the defined range of ±2% U_n [1], the controller increases the reactive power feed-in of the inverter, which has the highest impact on the critical voltage, according to [1]. If that inverter is already feeding in its maximum reactive power, the controller alters the reactive power feed-in of the inverter with the second highest influence and so on. The maximum reactive power of an inverter is defined by the reactive power which is fed-in at $\cos(\varphi) = 0.9$ and nominal active power. This implies that it is possible for singular plants to feed-in with $\cos(\varphi) < 0.9$ if they are feeding in with less than nominal power. The technical standard for connecting generators to the medium voltage [1] demands using cos(φ) of at least 0.95. For the presented study it was decided to use cos(φ) = 0.9 to increase the effect of reactive power control at the most sensitive nodes. This method can be transferred to practice since present inverter are already capable of cos(φ) of 0.9.

Combining all plants, however, it cannot hold that $\cos(\varphi) < 0.9$. In the worst case, where all plants feed-in with nominal active power, $\cos(\varphi)$ equals to 0.9, but never less. $\text{Cos}(\varphi)$ is 1 (Figure 3), until any voltage criteria is violated. The reactive power to compensate voltage rise is raised as effectively as possible until all the plants are at their nominal active power. Reactive power feed-in starts at the inverter with the highest impact on the critical voltage and then selects the second best inverter. Therefore, the more reactive power is needed, the less effective it gets. In sum, $\cos(\varphi)$ is minimized at 100% of active power feed-in. Since the system is partially linear, no local maximums of reactive power feed-in occur and $\cos(\varphi)$ is never lower than 0.9.

Results

The algorithm described is used for the grid defined in Figure 1 and the results are presented in this section. Figure 2 shows the voltages at the grid nodes dependent on the relative active power feed-in of the plants.

Active power is simultaneously raised from 0 to 100% at all nodes. The voltage at PV6 reaches the limit of 102% U_n at 60% of nominal active power. At this point, without reactive power control, the capacity of the grid would be reached by voltage limitation. The controller increases grid capacity by avoiding a further voltage rise through reactive power feed-in. The relation of dU/dQ to dU/dP is minimal at the PV6 connection point. This implies that more reactive power is needed at this point for compensating a voltage rise than at any other. For this reason, the voltages at all the other connection points fall from 60% of nominal active power feed-in see Figure 2.

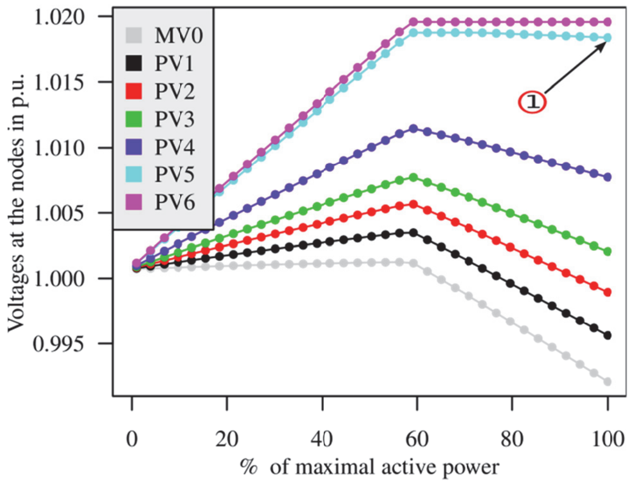

Figure 2: shows the node voltage in p.u. over the feeding active power. The red circles mark the points which will be used to configure the decentralized controllers.

In Figure3, reactive power is drawn dependent on active power feed-in. The characteristic behavior of the centralized controller is that PV6 increases reactive power feed-in until it reaches its limit, since it has the highest impact on itself. Then, PV5, with the second highest impact on the connection point of PV6, starts reactive power feed-in. Since the impact of PV5 is less, the gradient of the curve is expected to be higher. However, reactive power is given in percent of the maximum reactive power in Figure 3. Therefore, the observed gradient for node PV5 is smaller, since installed power is larger.

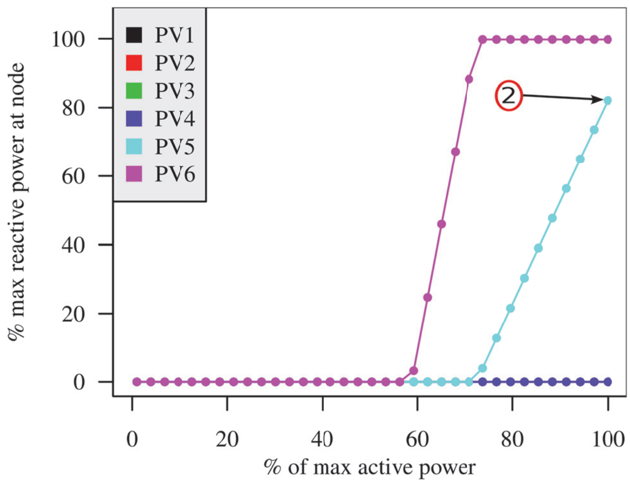

Figure 3: shows the percentage of the maximum reactive power that is fed into the grid. The red circles show the values which are needed for the configuration of the decentralized controllers.

DISTRIBUTED CONTROLLER

After calculating the optimal behavior of the centralized approach, the parameters for the distributed Q(U) controllers are derived.

Derive decentralized Q(U) controller

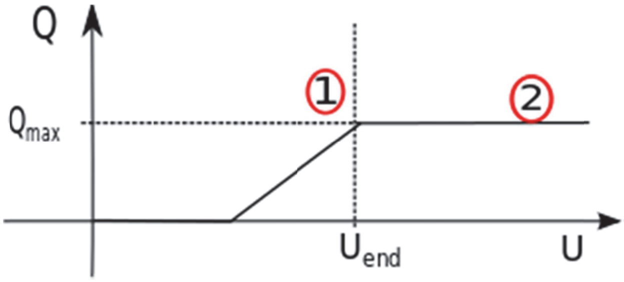

Figure 4: Shows the Q(U)-curve of the decentralized controllers. U_{end} and Q_{max}, marked as 1 and to 2, must be found with the help of the central controller.

The decentralized controller must maintain voltages within its boundaries at all times. As an auxiliary condition, it should spend as little reactive power as possible. Since a Q(U) static is sensitive to the voltage, it is possible to maintain it within its boundaries without using reactive power, when it is not required.
Therefore, the initial information from the centralized controller is that only PV5 and PV6 need to feed-in reactive power (Figure 2). Figure 4 presents two interesting points for the decentralized controllers.

Since the decentralized controllers only have the voltage at their connection points as information, it is necessary to find the voltage at which the maximum reactive power is fed in. The voltage, U_{end}, from where the maximal reactive power is fed-in, is marked with a 1. Since the voltage rises to its maximum and then falls until maximum active and reactive power feed-in is reached, the voltage at this point needs to be selected, see Figure 3. The maximum reactive power, Q_{max}, needed at this voltage is marked with a 2.

The decentralized controller would already reach its maximum reactive power feed-in at less than 60% of active power feed-in when no Voltage limit is reached at all. Therefore, reactive power production for the decentralized controllers is restricted by $\cos(\varphi)=0.9$ at each inverter. This still leads to too much reactive power feed-in until the active power limit is reached, but less than without the $\cos(\varphi)$-restriction.

SHOWCASE

Methods and parameters for the centralized and the decentralized reactive power controller have now been derived. In the following, this result is applied to a realistic PV generation profile.

Real PV-profile

In Figure 5, the PV-profile for which the central and the decentralized controllers are analyzed is shown.

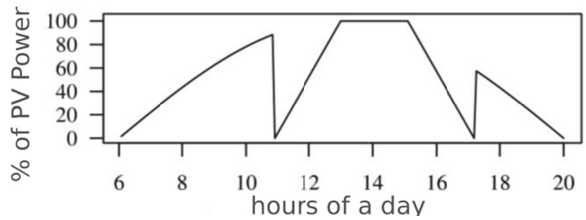

Figure 5: shows the PV profile for which the controllers are tested.

In Figure 6, the reaction of the grid with the centralized controller is presented. The controller handles the steps between 10:00 and 12:00 and between 16:00 and 18:00. The remaining results are as expected from the preceding definition.

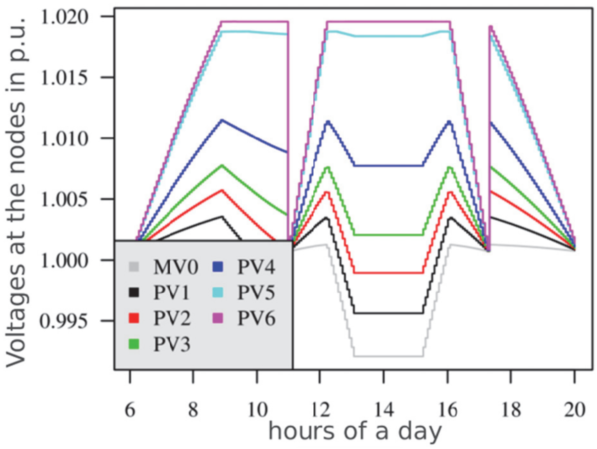

Figure 6: shows the voltages in the grid controlled by the central controller.

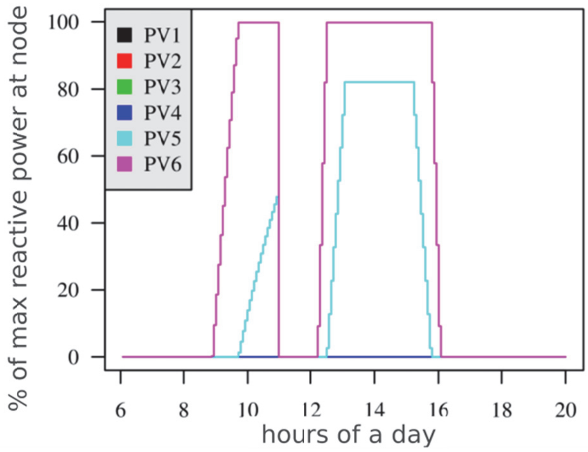

Figure 7: shows the reactive power feed-in by the inverters controlled by the central controller.

In Figure 7, the corresponding reactive power feed-in from the inverters is shown. During high PV feed-in,

large amounts of reactive power is needed for the compensation of the voltage rise. PV6 reaches its limit before PV5 starts to feed in and PV5 stops feeding in before PV6 starts to lower its reactive power feed-in, which is characteristic for the centralized controller.
In Figure 8, the voltages in the grid with the decentralized controllers are shown. At the first spike, the decentralized controllers start reactive power feed-in (Figure 9) before the voltage limit is reached. This is the reason for having a voltage profile which is strongly related to the PV-Profile of Figure 5.

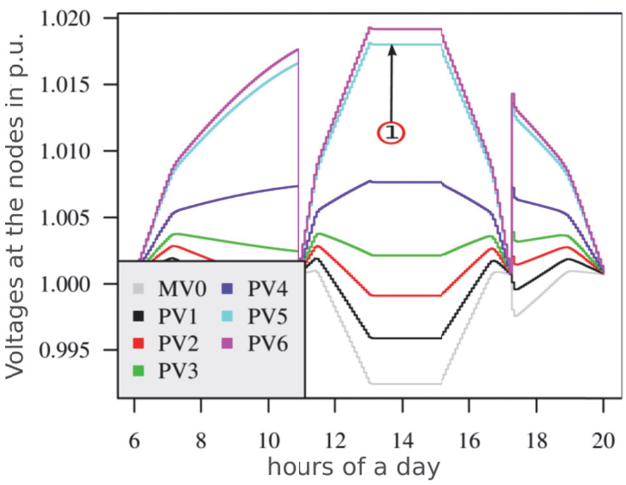

Figure 8: Voltages in the grid controlled by decentralized controllers placed in the inverters.

DISCUSSION

Comparing Figure 7 and 9, decentralized controllers produce more reactive power, since they start to feed-in at their voltage limits. Moreover, PV5 starts much earlier than in the centralized case.

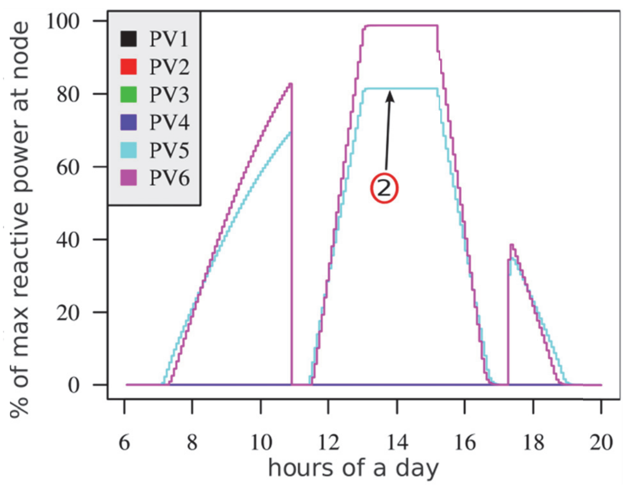

Figure 9: Reactive power feed-in by decentralized controlled inverters.

Regarding Figure 3, reactive power control starts to intervene at about 60% of maximal active power feed-in. Without control the grid would operate beyond its limits from this point on. This means that both possibilities to control reactive power increase grid capacity by more than 60%.

CONCLUSION

This paper presents an approach to parameterize distributed reactive power controllers in a distribution grid. By first using an optimal centralized perfect controller, it is possible to derive near optimally distributed controllers. Additionally, both controllers increased grid capacity by more than 60%.

This algorithm can be used during the planning process to define optimal parameters for the connected inverters to guarantee both optimal voltage stability and minimal stressing due to reactive power. In the vision of the Smart Grid, where communication to the generators is available, the parameters could also be changed if the grid structure changes, e.g. a new plant is connected.

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