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Methods

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Multivariable control of active distribution networks for TSO-DSO-coordinated operation in wide-area power systems

Mehrgrößenregelung von aktiven Verteilnetzen für die TSO-DSO Betriebskoordination von großen elektrischen Netzen

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Abstract: This paper describes a multiple-input, multiple-output distributed control concept for the operation of a distribution network. The concept aims to coordinate a set of distributed generators within the distribution grid to regulate the active and reactive power flow exchange with the transmission network and adjacent distribution grids. The control concept further aims to control the distribution network voltage profile such that voltages continuously remain within a predefined secure operation range. The implementation of such a concept can substitute for the decreasing flexibility in the transmission network which results from the decommissioning of conventional power plants in the future. As proof-of-concept, an implementation is tested through time-domain simulation.

Keywords: active distribution network, multivariable control, smart grid

Zusammenfassung: Diese Arbeit beschreibt eine verteilte Mehrgrößenregelung eines Verteilnetzes. Das Ziel ist der koordinierte Betrieb der dezentralen Erzeuger im Verteilnetz, um Sollwerten für die Blind- und Wirkleistungsflüsse zum Übertragungsnetz bzw. benachbarten Verteilnetzen zu folgen. Es werden des Weiteren alle Spannungen im Verteilnetz in einem vordefinierten, sicheren Band gehalten. Die Implementierung eines derartigen Konzepts kann den Verlust von Flexibilität im Übertragungsnetz ausgleichen, welcher mit der Ausserdienststellung konventioneller Kraftwerke einhergeht. Das Konzept wird durch Simulationen im Zeitbereich verifiziert.

Schlagwörter: Aktive Verteilnetze, Mehrgrößenregelung, Smart Grid

1 Introduction

Governments around the world have responded to environmental challenges resulting from fossil fuel consumption with a change in power generation to curtail the emission of CO_2. The current generation target agreed by the German government is to cover 80 % of electric power demand on the basis of renewables by 2050 [2]. This is recommended to result in the decommissioning of conventional coal-fired power plants by the end of 2038 [3]. Their synchronous generators are a core part of the current operation of the power system and with the decommissioning of these power plants, the burden of providing operational flexibility is shifted downstream to be provided increasingly by the distribution grids and their smaller, generally power-electronic-interfaced, distributed generators.

An active distribution grid (ADN) with a control infrastructure offers the potential to provide the operational flexibility needed for the operation of the power system. A transmission system operator would need no knowledge of the exact composition of an active distribution grid connected to the transmission network but would merely set reference values for the active and reactive power flow at the interconnection point. The active distribution grid would then autonomously maintain voltage limits at its internal buses. Such a control scheme for an active network was described in [7] and this paper will extend the existing research by allowing the control architecture of the active distribution grid to track reference values for an arbitrary number of TSO-DSO or DSO-DSO interconnections

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and by offering dynamic voltage control, as is illustrated in figure 1. In this fashion, the active distribution network can support the operation of the transmission network and that of laterally connected distribution networks.

The paper is structured as follows:

Section 2 gives a brief overview of proposed control schemes for active distribution networks.

Section 3 describes the goals of the proposed control architecture as well as the general structure of the system.

Section 4 describes the control architecture and the parameter synthesis.

Section 5 explains the test grid and shows simulation results.

Section 6 presents the conclusions and a summary.

2 State of current research

The idea of using the operational flexibility of distribution grids for general grid support is relatively recent. In general, control concepts for the future active distribution grid can be grouped under two different categories: a central control architecture, and decentralized controllers. Centralized approaches typically generate local generator control setpoints based on some range of measurement values in the grid like bus voltages, line loading, and transmission grid requirements at the interconnection points. A good introductory example for this type of ADN controller is the model predictive controller used in [4] to control DSO and (to a lesser degree) TSO voltages and the optimal power flow planning algorithm described in [5] to support the voltage quality at the TSO node. Iterative load flow calculations were used for reactive power balancing at the interconnection in [12]. A more advanced and general model predictive controller including stochastic forecasts of renewable generation was described in [9].

Research into decentralized concepts has tended to focus on the problem of decentralized voltage control or the minimization of active power losses, such as [8]. There are other limited approaches to the control problem. For example, [11, 13] use tap stagger operation to induce reactive power consumption in the distribution network in order to alleviate voltage violations.

More powerful decentralized approaches include the consensus approach elaborately shown in [6] for voltage control and frequency control inside the distribution network. In [10], a concept was developed which showed a distributed control architecture that provides frequency support while maintaining safe voltage limits.

The fundamental control strategy in this paper is inspired by [7], which outlined a control architecture for active and reactive power flow reference tracking at the interconnection point with the transmission grid. The herein presented research can be thought of as an extension or successor to that paper. The singular strength of the concept is the total design independence of the distributed controllers from each other, allowing generators to be connected and disconnected at will.

3 Structure of ADNs and control goals

The goal of the proposed control architecture is the tracking of active and reactive power reference functions at the distribution grid interconnections while maintaining operational voltage limits inside the ADN. This is illustrated in figure 1. Note

1. the upstream provision of desired power flows to the transmission grid.
2. the lateral provision of desired power flows to the neighboring distribution grid.
3. the voltages maintaining their operational limits inside the ADN.

The control algorithm itself is capable of tracking an arbitrary number of interconnections. Only two interconnections are shown in figure 1 because it functions as a schematic of the test system, which has two interconnections. Systemic features of the system are

1. medium-voltage level.
2. the presence of storages, generators, and controllable loads at each bus of the active distribution network. These collectively form the four-quadrant distributed generator of the bus, also shown in figure 5 later.

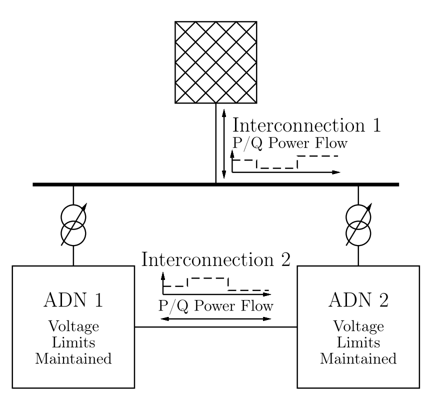

Figure 1: Schematic of Interconnections (All AC).

3. static P/Q loads at each bus and induction motors at some of the buses.
4. the presence of OLTC transformers at the interconnection of the distribution grids with the transmission grid.
5. the presence of a communication infrastructure.

A detailed schematic of the specific test system used is given in a later chapter in figure 6.

4 Controller

4.1 Control function

A note on terminology: In the context of this paper, the desired values for the TSO-DSO or ADN-ADN interconnection or the 1 pu voltage will be called a *reference* function or value and the desired injection from a single generator bus in the distribution grid will be called a *setpoint*. The latter is the output of the distributed controller, the former the input.

Classic multi-variable state space controllers are based on multiplying a controller row vector $\vec{K}$ with an error column vector $\vec{e}$ such that, w. l. o. g. for the one-dimensional output case

$$u = \begin{bmatrix} k_1 & k_2 & \dots & k_n \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ \dots \\ e_n \end{bmatrix}, \tag{1}$$

which can be thought of as an overlay of P-controllers scaled by the parameters k_i. An integrator can be added after this dot product for steady state accuracy, turning it into an overlay of I-controllers instead. It is this structure of the control law which we will mimic. Classic state space control methods would synthesize the controller parameters from the system matrices, but this would be too cumbersome here and a different approach is chosen.

Each bus in the ADN has a local controller which yields local generator setpoints P_{set} and Q_{set} for the active and reactive power injection at this specific bus based on the following control function in its Laplace transform:

$$\begin{aligned} P_{\text{set}} &= \frac{1}{s}\begin{bmatrix} \vec{K}_P & K_U(e_U)\Gamma(\vec{e}_P) \end{bmatrix} \\ &\quad \times \begin{bmatrix} \vec{P}_{\text{ref}} - \vec{P}_{\text{meas}} \\ U_{\text{ref}} - U_{\text{meas}} \end{bmatrix} \\ &= \frac{1}{s}\begin{bmatrix} \vec{K}_P & \underbrace{K_U(e_U)\Gamma(\vec{e}_P)}_{\text{Voltage Controller}} \end{bmatrix} \\ &\quad \times \begin{bmatrix} \vec{e}_P \\ e_U \end{bmatrix}. \end{aligned} \tag{2}$$

$$\begin{aligned} Q_{\text{set}} &= \frac{1}{s}\begin{bmatrix} \vec{K}_Q & K_U(e_U)\Gamma(\vec{e}_Q) \end{bmatrix} \\ &\quad \times \begin{bmatrix} \vec{Q}_{\text{ref}} - \vec{Q}_{\text{meas}} \\ U_{\text{ref}} - U_{\text{meas}} \end{bmatrix} \\ &= \frac{1}{s}\begin{bmatrix} \vec{K}_Q & \underbrace{K_U(e_U)\Gamma(\vec{e}_Q)}_{\text{Voltage Controller}} \end{bmatrix} \\ &\quad \times \begin{bmatrix} \vec{e}_Q \\ e_U \end{bmatrix}. \end{aligned} \tag{3}$$

These two control functions are responsible for both the active and reactive power flow reference tracking for all the interconnections as well as local voltage control of the generator bus. The vectors $\vec{P}_{\text{ref}}$, $\vec{P}_{\text{meas}}$, $\vec{Q}_{\text{ref}}$, and $\vec{Q}_{\text{meas}}$ are vectors containing the reference and measurement values for the interconnection points and are of dimension $n_{\text{interconnections}}$. The vectors $\vec{K}_{\text{P}}$ and $\vec{K}_{\text{Q}}$ are row vectors of dimension $n_{\text{interconnections}}$ and contain control scalars. The synthesis of these parameters will be described in the following chapter. The term $\frac{1}{s}$ is the Laplace-transformed expression of an integrator, which is necessary for steady state accuracy. The expression $K_U(e_U)\Gamma(\vec{e}_{Q/P})e_U$ supplies the local voltage control of the generator bus and its mechanics are described later in chapter 4.3. $\vec{e}_P$ and $\vec{e}_Q$ are the active and reactive power flow control errors for the interconnection points and e_U is the local voltage control error at the generator bus. Note the scope of these values:
1. P_{set} and Q_{set} are *local* setpoints for the generator bus.
2. $\vec{P}_{\text{ref}}$, $\vec{P}_{\text{meas}}$, $\vec{Q}_{\text{ref}}$, and $\vec{Q}_{\text{meas}}$ are *global* reference and measurement signals for the power flow interfaces.
3. U_{ref} and U_{meas} are *local* voltage reference and measurement signals.

By necessity, the control function must be output feedback; state feedback would be impossible without an extremely complex state observer, and computationally expensive as well. Only the system output is readily accessible. The signal flow of the control signal is illustrated in figure 2. From this structure it follows that the system contains as many controllers as there are generator buses, with all of them being equally privileged.

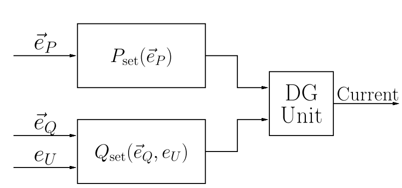

Figure 2: Control Signal Flow at Each Bus (Active Power Voltage Control Disabled).

4.2 Power flow control

The previous chapter described the general form of the control function as it generates a local generator setpoint. It does not explain how the entries of the vectors $\vec{K}_P$ and $\vec{K}_Q$ are obtained during controller synthesis, which is the subject of this chapter.

To understand the philosophy behind the parameter selection, consider a distribution network operating at steady state wherein a generator bus shifts its own injection slightly by $\Delta\vec{S}_0$ (the apparent power is used here as a generalized power flow). Assuming no line losses, this injection would reach the interconnections of the distribution grid as

$$\vec{a}\begin{bmatrix}\left\|\Delta\vec{S}_1\right\| \\ \vdots \\ \left\|\Delta\vec{S}_\text{n}\right\|\end{bmatrix} = \left\|\Delta\vec{S}_0\right\|, \tag{4}$$

where $\vec{a}$ is some unknown row vector of dimension $n_{\text{interconnections}}$, i. e., at a level of high abstraction, power flows will generally affect an electrically nearby interconnection more than a distant one. We consider the magnitude of the vector because the imaginary components of the electrical line will affect the composition of $\Delta\vec{S}$ and this is not of principal interest to us and will be regarded as a system disturbance. Note that here and in the future, we will denote the vector norm using $\|\vec{r}\|$ and the element-wise absolute value as $|\vec{r}|$. These operations are not identical.

Equation 4 is similar to the control laws in equation 2 and 3, by extension also to equation 1, and with some adequate normalization, the vector $\vec{a}$ could be used as-is as the controller vector K. Let us consider the active distribution network as a simple graph in which the edge weights correspond to the line lengths. In a practical system, the technical parameters of the lines per unit length would be very similar to each other at the same voltage level, something that is also reflected in benchmark grids, with only the length having a pronounced impact. Considering the buses as nodes and the lines as vertices, this leads to an undirected network graph. From this generalization, the entries of $\vec{K}_P = \vec{K}_Q = \vec{K}$ are derived from the graph as

$$\vec{K} = \left[\frac{1}{\text{sd}(g,i_1)+1} \quad \cdots \quad \frac{1}{\text{sd}(g,i_n)+1}\right] \tag{5}$$

from the source (i. e., generator node g to the interconnections $i_{1,2\ldots}$, with sd() as a shortest-distance search function such as Dijkstra's algorithm. In order to guarantee that all integrators are equally fast and to guarantee the robustness of $K_{\max}$ (which is described in the voltage control chapter), the controller vectors are rescaled to unit length, i. e., $\left\|\vec{K}\right\| = 1$. 1 is added to the denominator to avoid a division by zero should the generator node g contain the interconnection point.

Should the distribution grid contain lines with dramatically different technical parameters, then the simplest solution which conserves the functionality of the algorithm is a line length weighting factor b_i to weigh the relative electrical length $b_i l_i$ of the i-th cable. Only the relative electrical length to each interconnection is important, not the actual physical length, since the controller vectors are rescaled to unit length in any case; therefore such a line weighting factor can be introduced without harm.

4.3 Voltage control

Voltage keeping implies voltage behavior which remains within an acceptable band for all buses. It is not necessary to guarantee asymptotic stability, and attempting this would unnecessarily slow down reactive power flow reference tracking. Voltage control of a bus is done here by adjusting the reactive power injection. Should the voltage control error e_U grow too large, the generator bus shifts its injection such that the voltage stabilizes below a critical limit. Voltage control is included in the control function in equations 3 and 2. The voltage control parameter $K_U(e_U)$ is voltage dependent and contains a deadband around $e_U = 0$, whereafter it scales linearly within a critical voltage band to $K_{\max}$. This piecewise linear function is depicted in figure 3 and considering the integrator that follows according to equations 3 and 2, voltage control can be thought of as an I-controller with non-constant parameters overlaid onto the power flow controller. The parameter $K_{\max}$ must be chosen large enough that its contribution in the critical band begins to outweigh the parameters of the controller vector $\vec{K}_Q$ (which have, by definition, $\left\|\vec{K}\right\| = 1$). The function $\Gamma(\vec{e}_{Q/P}) = \max(|\vec{e}_{Q/P}|)$ is a scaling factor which scales e_U to be on the same order of magnitude as the largest entry of $\vec{e}_{Q/P}$. This is necessary to make the selection of a constant $K_{\max}$ meaningful relative to $\vec{e}_{Q/P}$.

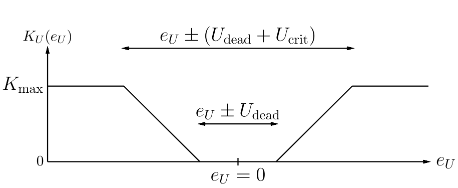

Figure 3: Voltage Controller Parameter $K_U(e_U)$.

The full voltage controller $\frac{1}{s}K_U(e_U)\Gamma(\vec{e}_Q)$ is essentially a variable-parameter I-controller. If the generator bus voltage leaves the deadband, the controller parameter becomes non-zero and the controller begins to stabilize the bus voltage by shifting the reactive power injection of the generator. When this happens, the controller parameter increases linearly and the bus voltage stabilizes on the ramp since $K_U(e_U)\Gamma(\vec{e}_{Q/P})e_U \geq \vec{K}_{Q/P}\vec{e}_{Q/P}$ with the choice of an appropriately large $K_{\max} > 1$.

In a medium-voltage grid, controlling the voltage is possible through reactive power injection alone. The benchmark test grid is medium voltage, and therefore the term $K_U(e_U)\Gamma(\vec{e}_P)$ will be set to zero in the simulations later shown. This substantially improves active power flow reference tracking.

5 Case study

The control architecture was validated using time-domain simulation and the test grid was based on the 14-bus, three-phase, medium-voltage CIGRE test grid defined in [1] and shown in figure 6. The voltage levels that define the TSO-DSO interconnection vary by country, and in the interest of consistency, we will adhere to the diction of the CIGRE benchmark document and use the 20 kV–110 kV levels. It does not affect the algorithm.

The graph of this grid, as used for controller synthesis with graph weights given in kilometers of electrical line, is shown in figure 4. Generators are each limited to an apparent power of $4 \leq \|\vec{S}_{DG}\| \leq 8$ MV A randomly sampled from a uniform distribution. This yields a circular flexibility plane for the buses; this is considered permissible since generators, storages, and flexible loads are all controlled by each distributed controller. Reference signals are step functions also randomly sampled from a uniform distribution. These reference steps occur at $t = [15\ 20\ 30\ 60\ 70]$ seconds. The numeric simulation was performed in MATLAB/Simulink using Heun's method and a 1 ms time step. The voltage controller maximum is $K_{\max} = 10$, the deadband was ±3 % and the critical voltage was ±6 % of 1 pu.

The influence of the communication infrastructure was reflected by delaying all setpoint signals with a 10 ms time delay and a PT_1 transfer delay with a time constant of $T = 0.1$ s.

The system response to the time-varying power flow reference functions was simulated for 90 s. The generation limit of the buses and their distributed generators is shown in figure 5. The active and reactive power flows between the active distribution networks and the upstream transmission grid as well as between each other is shown in figure 7 through 11. The bus voltage levels are illustrated in figure 12 with one line per bus and the OLTC positions are shown in figure 9. The fluctuations in the power flow occur when the other interconnection is subjected to a reference step and the controllers need to find a new equilibrium. Voltage control behavior can be observed after the reactive

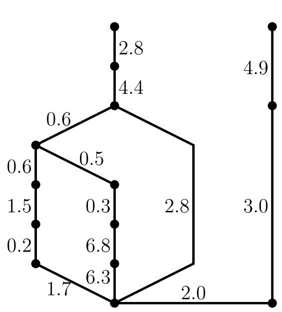

Figure 4: Network Graph of Figure 6.

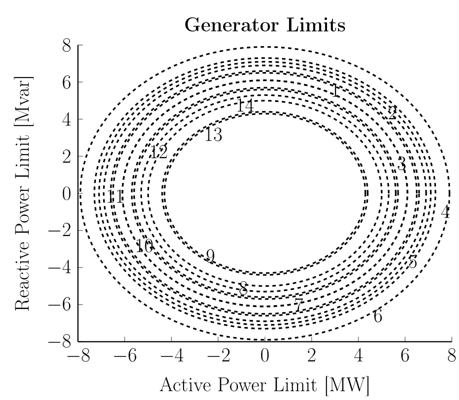

Figure 5: Generator Apparent Power Limits.

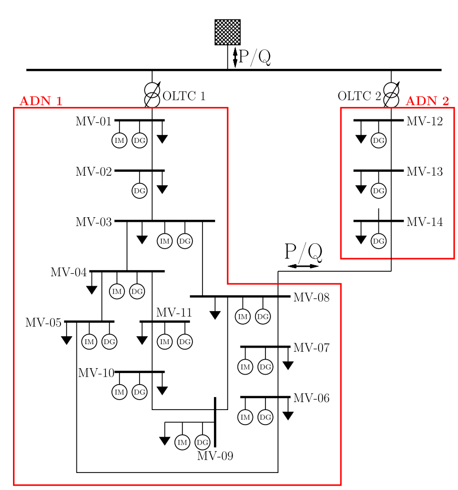

Figure 6: Test Grid with ADNs.

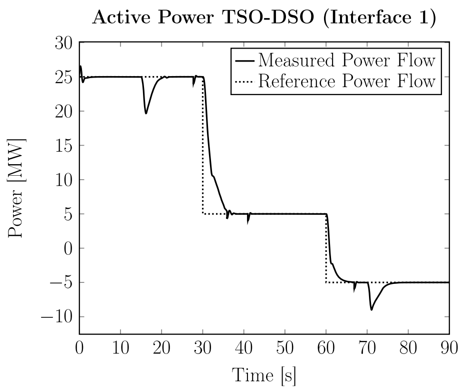

Figure 7: Active Power Exchange with TSO.

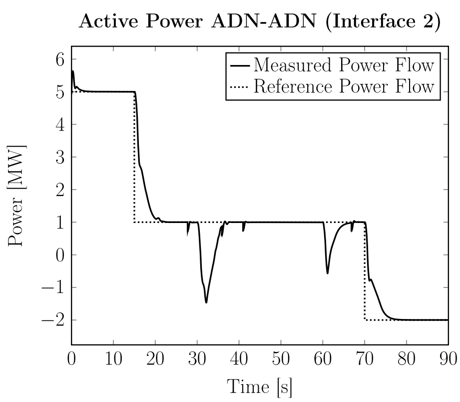

Figure 8: Active Power Exchange between ADNs.

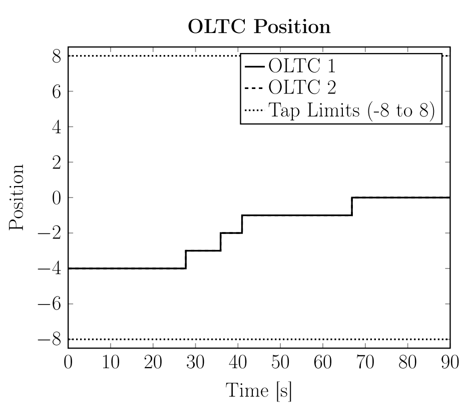

Figure 9: OLTC Positions.

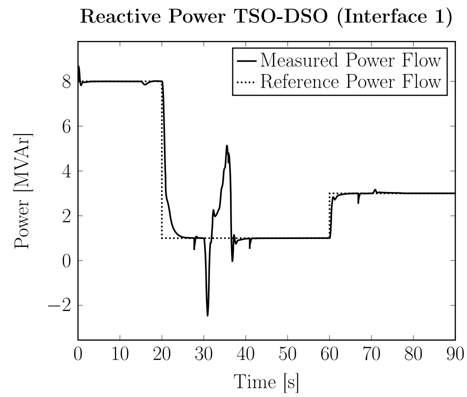

Figure 10: Reactive Power Exchange with TSO.

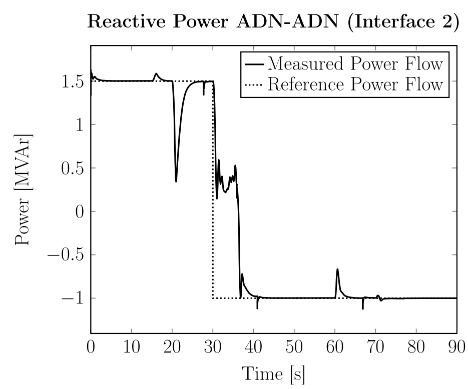

Figure 11: Reactive Power Exchange between ADNs.

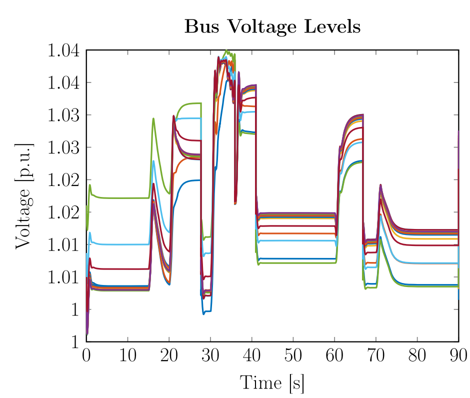

Figure 12: Voltage Levels of All Buses.

power flow reference step at $t = 30\,\mathrm{s}$. The buses approach the overvoltage limit; at this point the voltage controller begins to curtail further integration of the reactive power flow and instead stabilizes the voltage below the critical value. Once the transformer steps up, voltages fall and the controllers can reattempt tracking the reactive power flow reference value. Since the buses do not leave the voltage deadband simultaneously, their voltage controllers also become active at slightly different times, leading to the observed voltage convergence, and the delays in the communication infrastructure generate low-amplitude oscillations as $K_U(e_U)$ is not constant in this operational regime.

6 Conclusions and summary

A controller architecture was shown which could provide operational flexibility to the transmission system operator or neighboring distribution systems by tracking reference functions for the power flow interconnection while respecting internal voltage limits for its buses.

A fundamental advantage of the proposed controller is its total design independence; as long as the generator limits are on the same order of magnitude, there is no necessity for a swarm consensus as controllers have enough authority to maintain local voltage limits until the distribution grid reaches the edge of its operational envelope. The lack of any central architecture means that generators can be connected or disconnected with no integration into each other and no redesign of a central control architecture. This makes the proposed distributed control architecture highly scalable and robust against the loss of control authority in some of the nodes.

The presented research can be extended in various direct and indirect ways. Consensus dynamics among the controllers can be used to improve grid tracking performance. The generators were also assumed to be uniform in terms of dynamic behavior, which is not necessarily the case as the various forms of renewable energy generation and flexibility like solar, wind, batteries, power-to-gas, and power-to-heat work at different timescales and would therefore respond differently to the setpoints submitted by the local controller. This would entail a fair amount of more detailed modeling.

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