ADVANCED COORDINATED VOLTAGE CONTROL STRATEGIES FOR ACTIVE DISTRIBUTION NETWORK OPERATION

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ABSTRACT

An advanced approach for voltage control in distribution networks is introduced that allows the number of DERs (Distributed Energy Resources) connected to a distribution network to be increased. This contribution discusses the approach comprehensively with simulation results and guidelines for practical implementations. The methodology presented attains the objective of controlling the voltage in distribution networks with high shares of decentralized generation while maintaining a good compromise between simplicity and performance. Possibilities of implementation in a demonstration phase are also presented.

INTRODUCTION

The connection of more decentralized energy resources (DERs) to the distribution network may lead to a voltage and/or current problem in the distribution network. The “fix and forget” approach works well only if a small number of decentralized plants are connected to the network. If the number is increased, other measures have to be taken into account.

As far as the voltage problem is concerned valuable countermeasures are appropriate control strategies. These control strategies counteract the over- or under-voltage in the network by acting reasonably on the actuating elements. The actuating elements of the control loop are a 110kV/30kV on-load tap changer (OLTC), the produced reactive power of the decentralized plants and as an “ultima ratio” measure the active power of the decentralized plants. The control activity has to be carried out coherently, meaning that the control activities should not unnecessarily limit the operation of the distribution network and should take into account the physical limits of the contributing decentralized plants, since plants can produce only a certain amount of reactive power and excessive curtailment of the active power would limit the plant’s profitability. Therefore sophisticated and comprehensive control strategies have to be devised that work reliably under a variety of different network operating conditions.

The control strategies here presented are based on an evaluation of the voltage of “critical” nodes in the distribution network. Critical nodes are nodes within the network where the voltage is critical for the operation of the network. Using state machine evaluation concepts, appropriate control actions are chosen in order to bring the voltages of the critical nodes within the acceptable voltage band. Control actions are changing the tap of the on-load tap changer of the transformer, the production of additional reactive power at the plants, and the curtailment of the active power production of the plants. The production of additional reactive power and the curtailment of active power of the plants are minimized as far as the time horizon of the control action is concerned and as far as the amount of production or curtailment is concerned. A very helpful method to determine the necessary control actions has been developed. It is based on contribution matrices for reactive and active power which reflect the effect of additional power generation or consumption of the decentralized plants on the voltages of the critical nodes. Critical nodes and the corresponding contribution matrices are determined by offline simulations of the distribution network under study.

DISTRIBUTION NETWORK TOPOLOGY

A typical distribution network topology is shown in Fig.(1).

Figure 1: Exemplary distribution network topology

The distribution network is connected to the transmission network by a transformer usually with an on-load tap changer. This tap changer usually is for compensation of the voltage fluctuations in the transmission network. The controller of the on-load tap changer therefore measures the voltage of the bus bar in the transformer station and controls...
the set point of the on-load tap changer accordingly. For our purposes, the controller of the on-load tap changer gets the set point from our central coordinated voltage control unit (CVCU) and is used to optimize the voltage of all critical nodes in the distribution network. Critical nodes are nodes in the distribution network where the variation due to load and generation variation leads to critical node voltages for the operation of the network; they are typically found by simulation.

Within the distribution network we have loads and generators, denoted on the schematic by dark and white dots, respectively. Some of the generators are controllable, meaning that our controller can change their active and reactive power if necessary; these are denoted by thick circles on the schematic. Within this distribution network the voltage of each bus bar should be within an acceptable band, for example between 0.94 p.u. and 1.03 p.u. (data provided by a network operator). In networks with a high share of DERs without countermeasures this band may be violated. To prevent this, the CVCU changes the actuating elements (tap changer, and active and reactive power of the controllable DER).

THE CONTRIBUTION MATRIX APPROACH

In order to describe the variation of the voltages of the critical nodes with respect to the active and reactive power of the controllable DER, the contribution matrix approach is introduced. The contribution matrix is a linear mapping from the variation of the active and reactive power of the controllable DER:

$$\Delta U_{CV} \approx A_P \Delta P + A_Q \Delta Q$$  \hspace{1cm} (1)$$

where $\Delta U_{CV}$ is the variation of the voltage vector of the critical nodes, $\Delta P$ the variation of the active power vector and $\Delta Q$ the variation of the reactive power vector of the controllable DERs. $A_P [n \times m]$ and $A_Q [n \times m]$ are the contribution matrices for active and reactive power respectively. $m$ and $n$ are the number of critical nodes and controllable DERs respectively. The coefficients of these matrices can be considered as voltage sensitivity factors. Eq. (1) holds only if all loads are constant and if the power variations are small enough. This means that we have a tool at hand where we can estimate what influence the controller-proposed power variation has on the voltages of the critical nodes. A very important question is whether or not the linearity that Eq. (1) describes holds for a broad variation range with constant coefficients of the contribution matrices. Therefore, we simulated a big distribution network in the westernmost state of Austria, Vorarlberg, and observed how the coefficients of the contribution matrices varied over one year using actual load and generation profiles. Results show that the error by introducing contribution matrices with constant coefficients is very low. Additionally, in order to improve accuracy, the coefficients of the contribution matrices can be adapted depending on the voltages of some critical nodes. Last but not least, we will devise controller strategies that do not heavily rely on the precise estimation of the voltage variation of the critical loads but use Eq. (1) merely as a guideline for optimization and control. Furthermore, future systems will use state estimation even in the distribution network; this will make online estimation of the contribution matrices possible.

CONTROL STRATEGY

The basic principle behind our control strategy is shown in Fig.(2)

At each time step, the CVCU reads the voltages of the critical nodes. (If necessary, the voltage of the critical nodes could be sampled at a higher rate and some kind of signal conditioning applied.). A state machine, and possibly also a constrained scenario-specific optimization algorithm, are applied to the voltage data to determine and carry out control actions.

State machine

The state machine basically imitates a human operator and organizes the controller actions in a hierarchical way. It consists of four states:

- "Evaluation" state: the voltages of the critical states are evaluated
- "Tap changing" state: if possible and necessary, a new set point for the on-load tap changer is set.
- "Q regulation" state: if tapping is not possible and variation of reactive power of the controllable DER is sufficient, the controllable DER gets a new reactive power demand.
- "PQ regulation" state: if Q regulation alone does not bring the voltages of the critical nodes back within the acceptable voltage band, active power of the controllable DER is reduced and the reactive power is set appropriately. It minimizes reduction in active power by maximizing changes in reactive power.

Between these states appropriate transitions are devised. In
Fig. (3) the state machine with the states and transitions is shown. Transition 7 and transition 10 are special transitions that deserve special mention.

**Figure 3: State machine**

Transition 7 is activated if the voltages of the critical nodes are within the voltage band, some of the DERs generate additional reactive power, and the optimization procedure of the controller determines that reactive power can be reduced without violating the voltage band. Transition 10 is activated if the voltages of the critical nodes are within the voltage band, some of the DERs are curtailed as far as their active power production is concerned, and the optimization procedure of the controller determines that active power can be increased without violating the voltage band.

**Constrained optimization**

Constrained optimization is used in order to optimize the control actions during “Q regulation” and “PQ regulation”. The constraints stem from the fact that the reactive power limit depends on the active power of the plants: there are limits from the maximal apparent power and the minimal power factor. Additional constraints coming from the voltage band also must be observed. Optimization guarantees that, in the case of “Q regulation” and “PQ regulation,” the minimum reactive power demand and active power reduction, respectively, is applied to guarantee the voltage band.

For “Q regulation” we state the optimization task explicitly:

\[
\begin{align*}
\min & \text{ sum}(|\Delta Q|) \\
\text{under} & \\
U_{\text{min}} & \leq U_{CN} + \Delta U_{CN} = U_{CN} + A_{\phi} \Delta Q \leq U_{\text{max}} \\
\text{and} & \\
Q + \Delta Q & \leq P^\ast \tan(\phi_{\text{max}}) \\
\text{and} & \\
Q + \Delta Q & \leq \sqrt{S^2 - P^2}
\end{align*}
\]

where the vector variables are:

- \( U_{CN} \) is the critical node voltage
- \( \Delta U_{CN} \) is the voltage variation due to the reactive power of the controllable DERs
- \( Q \) is the reactive power of the controllable DERs
- \( \Delta Q \) the variation of the reactive power induced by the optimization algorithm.
- \( P / S \) are the current/maximum active power of the controllable DERs

All inequalities are understood in a vector sense.

Intuitively, this suggests that we change the reactive power of the controllable DERs as little as possible in order to bring the voltage of the critical nodes within the allowed voltage band and observe the reactive power limits of the plants.

If this optimization has no solution because the change in reactive power is not sufficient to bring the voltage back into the allowed band, PQ regulation must then be applied.

**Principles of the controller**

The proposed controller strategy realizes the following principles:

- The controller should influence the distribution network operation as little as possible.
- The controller strategy is a compromise between simplicity, robustness and the required task (that is, increasing the share of DERs in an existing distribution network).
- The controller is based on a very approximate model of the distribution network, as represented by contribution matrices.
- The controller does not rely heavily on the accuracy of the model.
- The controller design is based on optimization of the controller actions; it tries to reach a global optimum by the use of its available actuators (on-load tap changer and active and reactive power changes of the controllable DERs).
- The controller tries to keep the reactive power of the controllable DERs at zero if possible or the reactive power is chosen to guarantee the local reactive power compensation.
- The controller minimizes the curtailment of active power of the controllable DERs as far as the amount and the duration is concerned.
- Limits from maximal apparent power and the minimal power factor are observed.
- The controller is characterized by soft operation: if the control target is achieved, the active and reactive power demand of the controllable DERs is still applied unless there is a change in the voltages of the critical nodes that make a change in demand possible or necessary.
SIMULATIONS
A lot of simulation work has been carried out. Due to size constraints, we show here one special control situation (Fig. 4). The distribution network under study consists of 6 critical nodes. The voltage of the nodes are shown in the upper left graph.

![Simulation results](image)

In case of partial grid failure, some of the critical nodes could be supplied by another transformer. The CVCU and the underlying communication links should be smart enough to determine this new configuration and adopt its control strategy accordingly.

IMPLEMENTATION ISSUES
The controller strategies presented should be implemented as soon as possible. Therefore implementation issues must be discussed. Firstly, the distribution network must be modelled. With the help of classical load flow analysis tools the critical nodes must be determined and the distribution matrices computed. Some clustering methods have been devised to alleviate this task.

Apart from this issue, hardware enhancements to the system are needed. Reliable communication links must be established between the critical nodes, the DERs, and the CVCU.

In order to keep complexity low, a step-wise approach is envisaged where first the algorithm that controls only the on-load tap changer are used on a real distribution network.

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