REACTIVE POWER MANAGEMENT BY DISTRIBUTION SYSTEM OPERATORS CONCEPT AND EXPERIENCE

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ABSTRACT

In Germany the majority of renewable generation is connected to the distribution network level which includes low voltage up to high voltage level. The infeed of this power can cause an unacceptable voltage rise. The required additional network equipment, e.g. lines, generates reactive power if they run idle. Reactive power is also required to transport this power in the transmission network.
If distribution system operators (DSO) control the reactive power locally, the decentralised generators (DGs) can contribute to reduce the mentioned problems.
In the paper a concept of a reactive power management system is presented as it is developed by a joint work of 5 DSO in Germany. Results of the practical implementation of the 1st stage are demonstrated. Algorithms to improve the system in a 2nd stage are presented.
DGs in the high voltage level can be used to compensate the reactive power from the lower voltage levels and even improve the balance to the transmission system. An overall optimisation combined with a local voltage limiting functionality is essential to use a high portion of the potential by still keeping the network in a safe operating condition.

INTRODUCTION

In Germany more than 97 % of the generation from renewable sources onshore is connected to the distribution network level [1] with an increasing share. Within the country a generation surplus can be found in the northern and eastern part whereas load is concentrated in the southern part.

The injection of power from large wind or solar power plants in distribution networks with large geographic extent and low load can cause an unacceptable local or transregional rise of the voltage in these networks. If there is no generation the capacitances of the idle lines also cause a voltage rise. Both problems can be reduced, if reactive power can be provided by the generation units according to the requirements of the grid. Consequently it is the task of the distribution system operator to locally coordinate the reactive power behaviour of network equipment, load and generation. Especially in the high voltage level the DSO is in the position to simultaneously solve different tasks like voltage control, reactive power balance and management of reactive power provision to upstream transmission networks to support the reactive power requirements for the long distance transmission.

A working group was established consisting of 5 high voltage DSOs and one transmission system operator, all of them highly affected by the integration of renewable energy, in the eastern part of Germany to develop a joint solution to the mentioned challenges. The results of this work and first experiences with the implementation and operation are presented in the paper.

The reactive power management is implemented in two stages. In the first stage the necessary control functionality and connections to the generation units are implemented. The control itself is conducted manually by the DSO via telecontrol. In the second stage an optimization algorithm is developed and in implementation. It optimizes the distribution of the reactive power within the network taking the voltage limits and network equipment load into consideration and provide the maximum reactive power potential from a DSOs high voltage network group. A detected possible solution for such an algorithm is described within the following chapters.

POTENTIAL OF REACTIVE POWER FROM HIGH VOLTAGE NETWORK GROUPS

In the low and medium voltage networks a high number of relatively small wind and solar parks is connected. Usually they are erected far from the substation which causes local voltage increase in situations of high active power infeed. Because of this it is necessary to use reactive power potential of DGs in medium and low voltage levels to keep the local voltage distribution within certain boundaries.

For a full effective reactive power management across all voltage levels in future a lot of additional information about the network state, e.g. voltage values and power flows in neighbouring parts of the medium voltage (MV) network can be required also in these lower voltage levels. The necessary measurement devices together with the communication infrastructure are currently not in place and would need to be installed.

Therefore at the current stage a robust reactive power management is necessary although it might not lead to a perfect reactive power distribution. In these voltage levels for example a cos(φ)=f(P)-curve is provided to the generators. The shape and the limits of the curve depend on the situation in the particular network. For limiting voltage increase it is possible to implement Q(V)-characteristics to the DG, too. Therefore these wind farms and solar parks will not contribute to a reactive power management via telecontrol but surely have to be taken into consideration when designing the reactive power management system for the DSOs network.

Parks which are connected directly to a high-/medium-voltage substation or to the high voltage level do not necessarily need to use their reactive power capabilities to compensate the voltage rise caused by themselves. Their reactive power capabilities can be used to

- compensate the reactive power requirements from DGs in lower voltage levels (which these units inject to compensate their self-induced voltage rise)
- compensate the reactive power caused by the power flows within the network
- compensate the reactive power caused by the network elements (e.g. cables, transformers)
- optimize the voltage profile
- reduce network losses
- balance the reactive power to upstream networks (e.g. transmission network)
- provide reactive power according to the requests of the transmission network operator.

To reach these goals a reactive power management is mandatory which is described in the following sections.

Figure 1 displays the control potential of the reactive power of a 110 kV network group summarized at all points of common coupling. According to the current German standards this potential varies with the actual active power generation. Because of the reactive power caused by the internal network, especially transformers and the load flow situation belonging to each operating point, the potential is different from the totalized potential of all the individual generation units.

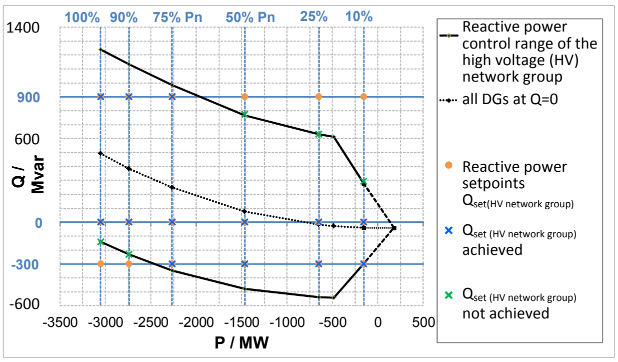

Figure 1: Reactive power potential from high voltage network group for reactive power management

Depending on the actual active power generation and resulting operating point some setpoints can be reached and some cannot. A control algorithm has to take the shape of the curve into consideration.

Another limit which is not shown in Figure 1 can be defined by the change of the local voltage due to the reactive power of the generation units. In most scenarios the voltage rise needs to be considered. Therefore a local voltage control is essential for using the full range of the possible reactive power potential.

Experiences in the networks of the participating DSOs showed that if the amount of connected active power is that high that it causes voltage problems then the potential of reactive power usually is sufficiently high to reduce the voltage rise to an acceptable value, too. Depending on the networks DG penetration, the point of coupling to the network, their size and commissioning date the potential of wind farms and solar parks can be sufficient to compensate the reactive power caused by the generation units in the lower voltage levels. In most of the network groups the potential is currently too small to significantly influence the voltage value on the 380 kV side of the 380/110 kV transformers but it can support the transmission system operator by reducing the reactive power demand of the connected distribution network.

CONCEPT OF REACTIVE POWER MANAGEMENT

The reactive power of a DG which means a total wind farm or solar park can be controlled aiming at two goals:

- "grid compatible behaviour" – the unit compensates some self-induced effects to the network at the connection point. An example is the operation following a cos(φ)=f(P)-characteristic to reduce the voltage rise caused by own active power injection at the connection point. It acts locally and does not take the effects of other generation units into consideration.
- "system compatible behaviour" – the unit compensates some aggregated effects to the power system. Some of the effects can be related directly to this generation unit e.g. the local voltage rise caused by the active power injection. Most of the effects can be related to the DGs as a whole but not directly to a certain unit, for example the voltage rise by a number of generation units connected to one feeder or the reactive power caused by the power flow over the transformers in substations. One control possibility can be a Q=f(V)-functionality to reduce the voltage rise in a feeder caused by all generation units connected to this feeder, not only the one under consideration. Another one can be the control of the reactive power distribution by a central institution which is described in this paper.

This central institution determines the optimal reactive power distribution in a high voltage network. It uses information about the distribution of the voltages in the network, the active and reactive power flows in the lines and transformers, the current and expected generation by

DGs, the transformer step settings and the reactive power capabilities of the generation units as well as the compensation equipment, if available. Based on this information it tries to find a setting of operation points for each of the generation units which complies with the following criteria:

- At no point in the network the voltage limits are violated. This includes not only the connecting points of the generation units but also the substations and all other parts of the network as well as the 380 kV-network. Voltage limits may also not be violated, even if a (n-1)-event occurs or if the generated power changes as predicted.
- The reactive power flows in the network are minimized.
- The reactive power behaviour of 110 kV network group to the upstream transmission network is either balanced or as requested by the transmission system operator.

The central institution has to be located in the DSOs network control centre as it is the only point where all the required information is collected.

The goal of the investigations performed by five DSOs, one transmission system operator and one consulting company was to develop a reactive power management system which can be implemented to solve the described tasks. As up to now there is only few experience with many of the effects of the reactive power control in interaction with volatile generation and load under real life network operation, it was decided to implement the reactive power management in two stages.

In the first stage the central institution is the network operator. He manually determines the setpoints for the reactive power of the individual generation units. Currently Q-setpoints, cos(φ)-setpoints or voltage-setpoints in conjunction with a Q=f(V) functionality are mainly used. Based on his experience the network operator can take the current and expected network state into consideration. He also can react on unexpected situations. This way he will get experience on how certain control operations influence the network situation. On the other hand he can observe and control only a limited number of generation units. Therefore he will focus on the control of few large wind or solar parks with high effects on the voltage and reactive power balance.

In the second stage the central institution is a closed loop control algorithm that is implemented in the network control centre. It calculates an optimal reactive power distribution based on a closed loop control process and generates the setpoints for the individual generation units. The control units of the individual DG then try to reach this setpoint. If the local control unit expects a violation of voltage limits because of the centrally given setpoint value it changes the reactive power behaviour such that the voltage stays within the limits. The central closed loop control algorithm then iterates the reactive power distribution to reach a solution that meets the setpoint and does not violate voltage limits.

FIRST EXPERIENCES WITH PRACTICAL IMPLEMENTATION

The first stage, manually determining the setpoints of the reactive power by the control centre, is implemented. First experiences show that the remote connection to DGs is subject to very different qualities and availabilities. It is important that the DSO carries out an appropriate monitoring up to the individual remote control systems and initiates measures in case of failure or inadequate availability. One way to improve the situation is to use the DSOs owned communication networks and implement the required data points by connecting the DG to the DSOs network. An alternative way might be the use of redundant data connections.

It is also recommended to perform acyclic tests to check the correct function on the DGs reactive power control unit. Especially after retrofits, fault remedies, maintenance on the plant side and also after scheduled disconnection an increased defect stock can be observed. In order to further increase the availability of the remote-operation technology of the DG, the use of a sufficiently dimensioned UPS is to be provided. In result, the short-term controllability can be increased. Furthermore, the remote control unit should assume a defined state when there is no voltage or no telecontrol connection available. The value Q=0 Mvar can be used for this. It is also possible that DGs control units transmit false measurements or react unexpectedly because of this. Therefore it is necessary to make plausibility checks within the control units by themselves.

For older parks it is not compulsory to provide reactive power according to the requirements of the grid. Often they have not installed the communication and control equipment to be able to upgrade to the current requirements. Cost of retrofitting would be too high, especially since there is not really an incentive for them to upgrade their equipment. In mixed parks referred to their date of commissioning only some of the units can sufficiently provide reactive power. Control algorithms have to take this into consideration and become more complex. For example no sufficient data can be provided for the algorithms as measurement devices are missing.

New parks should be able to provide reactive power according to the requests of the network control centre. But practical tests often show that the parks do not behave as requested. The error analysis shows that, for example, the measured values for the reactive power supply are used on the wrong voltage level or the sign is interpreted incorrectly. In [2] some typical error sources of DG reactive power provision and their impact on grid operation are presented.

Another experienced behaviour is shown in Figure 2. Esp. the monitored overexcited behaviour in situations when high voltage values are already detected may lead to unacceptable voltage increases (red crosses). The illustrated behaviour was caused by a scheduled disconnection of the unit from the DSOs 110 kV grid and after reconnection the DGs control unit did no longer memorize the setpoint value or a defined state value for reactive power. Beyond that for some operating points a very high slope of the characteristic curve and too much underexcited reactive power provision were detected, too.

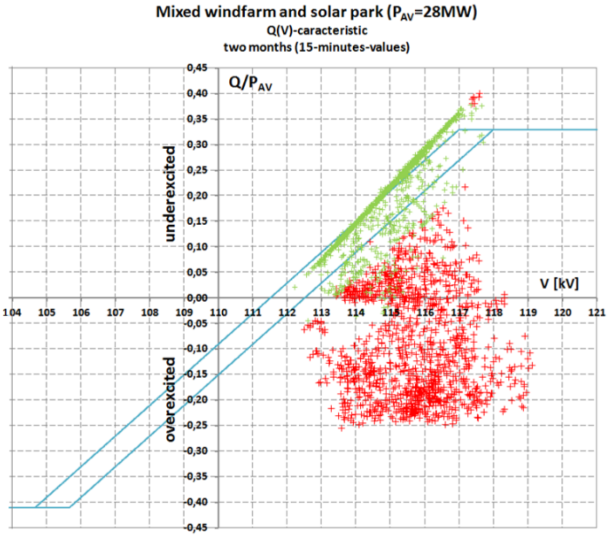

Figure 2: Reactive power provision from 110 kV connected DG unit with partly compliant Q=f(V) functionality

In addition to this, there already exist other communication links to the DGs control unit. In addition to the interface to the DSOs telecontrol system, there is another e.g. for the direct marketer, the technical operator or an interface for activating primary or secondary control reserve. It is also observed that these interfaces mutually interfere or overwrite each other. Even for the manual control a working and reliable communication connection is essential. Therefore the basic requirements for a reactive power management like the reactive power capability of the units, the communication connection and the availability of suitable controllers have to be determined in the technical requirements of the DSOs.

One problem with lines with high flows of reactive power together with low flows of active power is that distance protection devices can detect fault situations. It was verified, that for all possible load flow situations the operating point is outside of the pick-up polygon as shown in Figure 3.

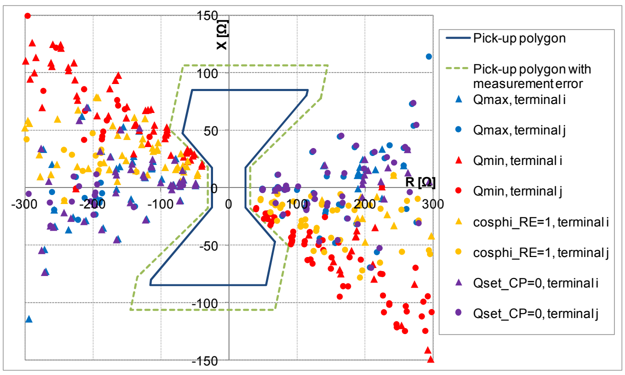

Figure 3: Operating points in distance protection diagram

This check is ideally performed in the DSOs network management system based on the estimated network state. The state in the disturbed (n-1)-state is particularly relevant. In the disturbed network state, higher reactive power flows result due to the increased load of the network equipment.

Depending on the voltage level and the protection concept of the DSO these states have to be taken into consideration. Critical states must also be calculated in forecast and have to be avoided in an optimization system.

OPTIMISATION SYSTEM

The optimisation system of the second stage consists of two main parts (see Figure 4). One is the central controlling unit (1). It is located in the distribution control centre. Based on the measurement data of the high voltage system it determines the optimal setpoints for the individual generation units within one network group (connected HV-network, can be fed by several substations from the transmission network). The second part is installed locally in each wind or solar park. It realises the voltage limiting functionality (5). If there is a danger of violating a voltage limit at the connection point it locally changes the reactive power value such that the voltage limit is observed (2). It overrides any value given by the central controller. This leads to a deviation from the central setpoint which forces the central closed loop control to changing the set point for all units until the central setpoint of the reactive power is reached.

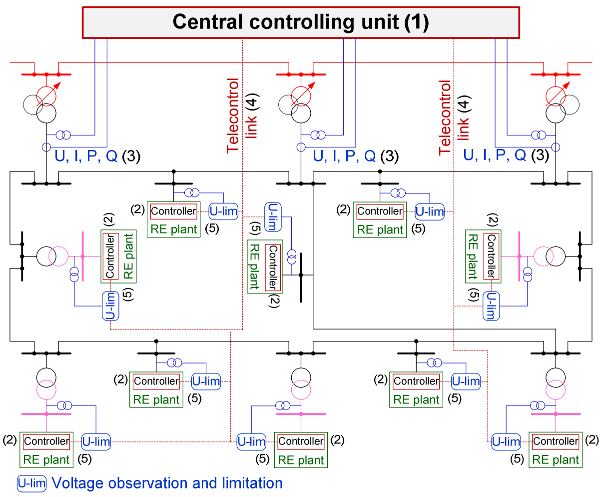

Figure 4: Principle of reactive power controller [3]

The optimisation algorithm can optimise to two targets:
Mode 1: optimisation of the power flows within the high voltage network without fulfilling certain requirements of the transmission network, minimizing losses
Mode 2: meeting defined reactive power setpoints of the transmission network at the connection point, accepting higher losses

The sole usage of Q=f(V)-characteristics does lead to a fair voltage profile but it is necessary to coordinate the central controller as well as the individual controllers with the tap changer of the EHV/HV-transformers. The sole usage of Q as a parameter neglects the possibility that voltage limits can be violated. But it is robust against voltage changes caused by the upstream network or the transformer tap changer. It does not cause transfer flows, too. Therefore a combination of Q-parameters with use of the tap changers to determine the voltage of the network group was chosen.

According to [4] it can take up to 4 minutes until an individual generation unit reaches a given Q-setpoint, but it can also reach it within seconds. Time constants of the central controller were set such that a stable convergence of the Q-value to the setpoint in the individual units is reached without the danger of oscillations.

Figure 5 shows the control behaviour with changing active power generation and simultaneous adjustment of the reactive power reference value to the actual grid situation. In the upper part of Figure 5 a time curve of the total active power infeed of all wind and solar power plants measured over 60 minutes is included. The lower part shows the time curve of the reactive power setpoints (red) and the reactive power (blue) actually occurring at the interface of the grid group.

The results show that the variable reactive power setpoints are adjusted each with a small time delay and high accuracy. It is apparent that changes in the reactive power balance of the grid group due to the change in active power infeed are completely adjusted if adequate control reserves are available. Otherwise, larger deviations occur between the actual value and the setpoint value of the reactive power, for example, as indicated in the diagram shown, between 40 min and 55 min.

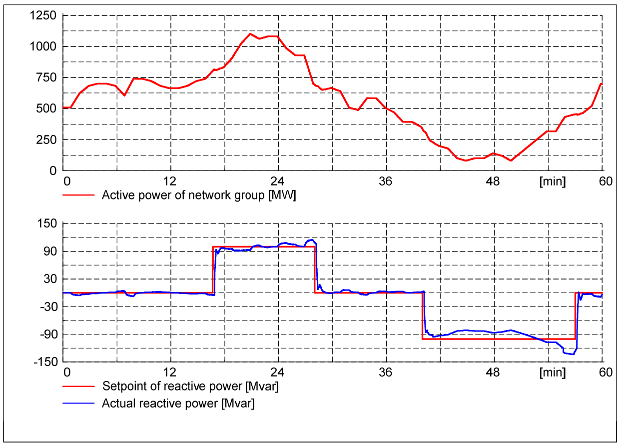

Figure 5: Results of Q-setpoint characteristic from DSOs high voltage network group

CONCLUSION AND OUTLOOK

In the paper a system for an active management of reactive power in distribution networks is presented. Even with a manual control of the reactive power of DGs the DSO has the opportunity to establish an instrument to ensure a fair voltage profile in the network. He can reduce the effects of the active power infeed of DGs to the network. He also can control the reactive power behaviour at the interface to the transmission system operator. With such a system an effective control of the reactive power behaviour of a network group is possible without impairing voltage conditions. Therefore the coordination of the response times of the individual generation units with the central controller is needed as well as the coordination with the DGs protection system, e.g. voltage increase protection. The settings of the individual controllers can vary and are not fully under control of the DSO.

First experiences also show the very high importance of the quality of DGs control units. So they have to assume defined state values when there is no voltage or no telecontrol connection available. Also plausibility checks within the control units by themselves are recommended.

So for successful implementation of an active management of reactive power the basic rules need to be determined in the technical rules of the DSOs. These rules have to be enhanced continuously taking into account the increasing number of generation units in the DSOs network levels.

Such a system is a substantial step in the development from a distribution network operator towards a distribution system operator. The timeline for the implementation of a central control unit as described in stage two mainly depends on the DG penetration in the DSOs networks and the voltage levels where they are connected to. The requirements of the transmission network for reactive power provision from DSO networks have to be identified first.

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