COORDINATED VOLTAGE CONTROL IN DISTRIBUTION SYSTEMS WITH DG – CONTROL ALGORITHM AND CASE STUDY

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ABSTRACT

Distributed generation (DG) in medium voltage distribution networks has become widespread during the last years. Distribution networks are normally planned and built to cope with decreasing voltage from the substation along the feeders.

With a high DG penetration the power flow can be reversed in some feeders during some time periods and thus the voltage increases along the feeder.

In this paper an improved voltage control algorithm for a more active voltage control in medium voltage networks is presented and tested by simulations in an existing network.

By using coordinated control of the DG units' active and reactive power as well as the on-load tap changer (OLTC), the DG hosting capacity can be increased without expensive network reinforcement. In the test case it was possible to increase the DG capacity from present 13 MW to 38 MW without the need of network reinforcements.

INTRODUCTION

Distributed Generation (DG) has become widespread during the past years. In the Swedish case this means primarily wind power, which is connected to the distribution grid at the 10 kV or 20 kV voltage level. Often the wind turbines are located in rural areas, where the grid in many cases is rather weak, since it is designed for low power transmission.

Traditionally distribution networks are planned and built to supply customer loads with electrical power. Under this assumption there are only unidirectional power flows from the substation to the customers. For the voltage in the network it means that the highest voltage will occur at the substation and then decrease along the feeders to the customers. The voltage drop is depending on the power, which is consumed by the loads, and by the line impedances.

If the DG capacity is increasing, the generated power from the DG units may exceed the power consumed by the loads during some time periods. In that case the voltage will no longer decrease but rather increase from the substation along the feeder. Due to the weak network, that the DG units are often connected to, their impact on the line voltage is rather high. With an on-load tap changer (OLTC) and a traditional controller set point at the substation this may cause voltages exceeding the limits at some busbars.

To keep the voltage at all network nodes within the limits all the time additional measures can be needed. Reinforcement of the network by building new lines is always a solution to reduce the voltage drop for pre-existing power. But that solution is expensive.

Another solution is a more flexible voltage control for distribution networks with a large share of distributed generation [1]. To obtain this a coordinated voltage control is introduced in this paper.

Voltage is controlled in three ways:

1) A variable set point of the Automatic Voltage Control (AVC) relay at the OLTC
2) Reactive power consumption by the connected DG units
3) Active power curtailment by the DG units if the first two methods are not sufficient.

Since many new wind turbines are connected to the grid by power electronic converters, they are able to control reactive power mostly independent from the active power output.

The voltage set point for the AVC should preferably use measurement of the actual network voltage at some busbars. The new generation of electricity meters, already installed in many places and equipped with communication, could be used to obtain voltage measurement directly from the customer side, where it is most important to keep the voltage within the limits given in e.g. EN50160 [2].

The algorithm for the coordinated voltage control, which was developed within this project, was tested on a rural network by simulations. The network data for the simulations are based on data from an existing network in the south of Sweden. Also the load and generation data used for the simulations were recorded from that network as minute by minute values. For the power flow calculations the MATLAB script framework MATPOWER 4.0 [3] was used.

TEST SYSTEM

For the case study a rural test system consisting of an existing Swedish medium voltage network with high DG penetration was chosen. Within the case study the amount of installed DG capacity was increased further to stress the coordinated voltage control.

The case study grid consists of totally eight 20 kV feeders with a total feeder length of around 130 km. One rather new feeder, where only generation is connected, is a pure cable feeder. The seven remaining feeders consist of both overhead lines and underground cables. That is a quite common configuration for Swedish medium voltage networks in rural areas, although the share of underground cables has been increasing during the last years.

In the network there are roughly 170 substations at the 20/0.4 kV level and three sub networks at 10 kV. The network feeders are of all three relevant types: pure load, pure generation and mixed load and generation feeders.

In the test system network the load varies between around 5 MW during low load periods and 28 MW at maximum load. So already in the existing network configuration the DG capacity, which is at around 13 MW, is that large that the generation at some low load periods exceeds the consumption. Thus from time to time the area has net production and a reversed power flow to the regional 130 kV network. Still, more generation units are expected to be installed in this area in the future.

In the extended network configuration which was used in the case study, the DG capacity has been increased further to stress the control algorithm. With the extended network configuration as used for the case study the generation capacity was increased from today's 13 MW to 38 MW, which was chosen with respect to the thermal limits of the lines. The profile for the total load and generation in the test case is shown in Figure 1.

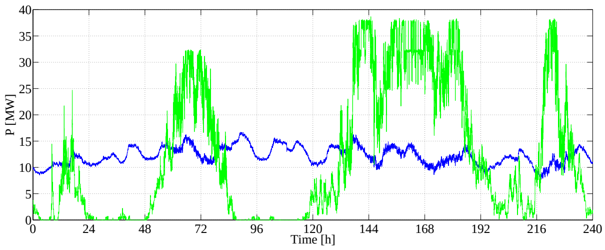

Figure 1 Load (blue line) and generation (green line) profile of the case study network with extended DG generation capacity over a time period of ten days (240 hours).

VOLTAGE CONTROL ALGORITHM

Since medium voltage networks were normally designed only for load, it was assumed that the network voltage is decreasing from the substation along the feeder to the load. The networks are dimensioned and built in such a way that the voltage drop along the lines is limited to an acceptable extent. Therefore voltage control by the AVC, which controls the OLTC at the substation transformer, is in pure load networks sufficient to keep the voltage within reasonable limits at all network nodes.

The situation may change considerably when generation is connected. In the case of reversed power flow as it can occur in networks with a high DG penetration, a decreasing voltage along the feeder is no longer necessarily valid under all operating conditions. By injecting purely active power at some busbar of the network, the voltage at that point will increase compared to the situation with only load. During periods of low network load the voltage rise caused by the injection of active power may result in a voltage higher than the one at the substation. In some cases even the upper voltage limit may be violated. Especially in mixed networks with both customers and generation connected to the same feeders this is an important issue, which can become a limiting factor for the DG hosting capacity of a distribution network.

Adapted control algorithms for the AVC to cope with networks, which have DG connected and thus increasing voltages, have been described in [4]. The introduction of a more active and coordinated voltage control seems to be a solution to increase the DG capacity with respect to the voltage limits and without the need of network reinforcement.

The control algorithm for coordinated voltage control consists of active and reactive power output control of the DG units and of a variable voltage set point for the AVC relay controlling the OLTC. An illustration of the coordinated voltage control and the components needed as they are used for the case study are shown in Figure 2.

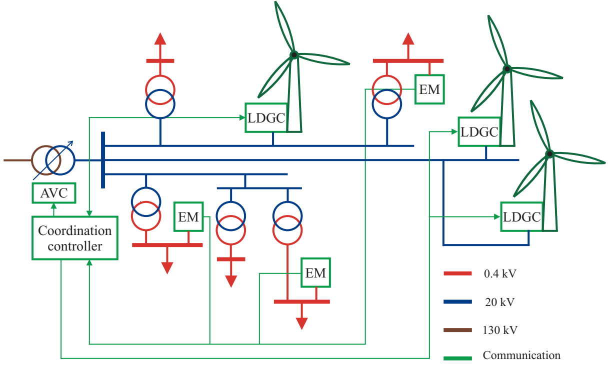

Figure 2 Schematic of a medium voltage network with the components needed for coordinated voltage control (AVC: Automatic Voltage Control, EM: Electricity Meter, LDGC: Local DG Control).

Modern DG units, such as many wind turbines, are often connected to the medium voltage grid by electronic power converters, which are able to deliver and consume an appreciable amount of reactive power mostly independent from the active power output. The variable power factor can be used to control the network voltage to some extent but may also increase losses. To limit the voltage rise also the use of active power curtailment is possible. Since active power has a high economic value, it should be avoided as long as possible. However, during short time periods, the active power curtailment may be a solution, when the benefits from an increase of the DG hosting capacity are larger than the costs for the curtailed energy.

For controlling the reactive and active power output of the DG units a voltage controller as shown in Figure 3 was used. As the DG units are only used to keep the upper voltage limit, there is no function for increasing the voltage implemented. In this case the local voltage controller for the DG units is behaving like a voltage limiter and the reference voltage V_{ref} is set to the upper voltage boundary, which has been chosen to 1.05 p.u.

Depending on the deviation from the set point the PI-controller is determining a set point for the active P_{ref} and the reactive power Q_{ref}. In the branch for the reactive power set point a saturation function is representing the boundaries of the reactive power output. The branch for the active power set point includes a dead band function avoiding active power curtailment as long as reactive power is available to satisfy the voltage constraints.

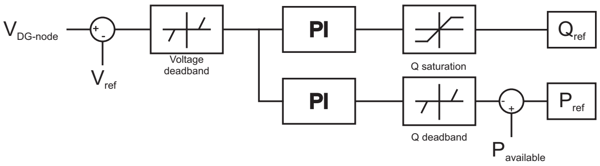

Figure 3 The local DG controller

Using the OLTC at the substation transformer more flexibly is another measure to make the voltage control of medium voltage networks fit to new challenges. Today the set point of the AVC at the OLTC is normally constant. The set point is chosen to keep the lowest voltage in the network above the lower voltage limit during high load situations. To some extent also line drop compensation is used. In that case the voltage level at the substation is depending on the current load situation in the network.

For determining the set point of the AVC the algorithm proposed in this paper takes the current voltages in the network obtained from the electricity meters at the customer side into account. By already having installed electronic electricity meters with communication in Sweden, the voltage at the customer side, which is the most interesting location, is remotely available.

The proposed voltage controller, illustrated in Figure 4, is determining a variable set point V_{sp} for the AVC relay.

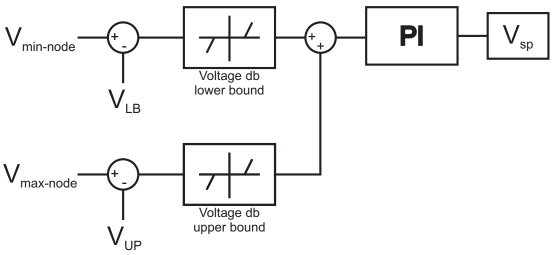

Figure 4 The local OLTC controller

In contrast to the local voltage control of the DG units this controller has to limit the voltage at the upper and lower boundary. The lowest voltage in the network $V_{min\text{-}node}$ and the highest voltage $V_{max\text{-}node}$ are compared to the lower and upper voltage boundaries, which are V_{LB} = 0.95 p.u. and V_{UB} = 1.05 p.u. respectively. Before calculating the set point a dead band function is used in each branch to avoid unnecessary tap changer operations and to ensure that either up or down regulating is activated.

Since only the voltage from the most exposed network nodes is needed, it should be sufficient to choose some relevant nodes in advance. In this way the amount of data, which is to be transferred from the electricity meters to the controller can be reduced.

RESULTS

For the case study the simulation of the network was run over a time period of ten days.

In the first case it was assumed that the voltage control is done by the DG units locally. The set point of the AVC relay is still constant. During times of high DG power output the upper voltage limit is reached at several network nodes. When the voltage is reaching the upper voltage limit at any network node where a DG unit is connected, the DG unit will start to increase the reactive power consumption. If the reactive power is not sufficient to keep the voltage within the limit, the DG unit will start to curtail the active power output as shown in Figure 5.

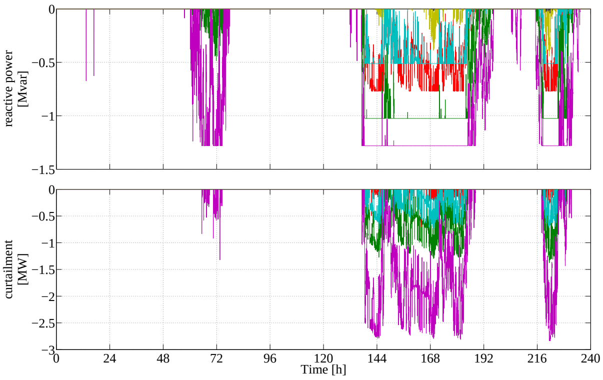

Figure 5 Reactive power consumption and active power curtailment from all wind turbines at the corresponding network nodes in the test system if only local control of the DG units is used to keep the voltage within the limits and the AVC relay set point is V_{sp} = 1.03 p.u.

To keep the voltage within the limits 213 Mvarh are drawn by the DG units in the network. The use of reactive power is as expected decreasing the network voltage. At some nodes this is still not sufficient to get the voltage below the upper voltage limit. Therefore beside the reactive power consumption another 146 MWh of active power have to be curtailed to get the voltage as low as needed to fulfil the voltage requirements.

Next the voltage control algorithm was extended with the coordinated control of the AVC relay voltage set point. Figure 6 shows the reactive power consumption when the set point of the AVC relay is adjusted to the actual network voltage as it is supposed to for the coordinated voltage control.

Compared to the case of only local DG control the amount of reactive power needed for the voltage control is heavily decreased (12 Mvar), which is reducing the network losses originating from the reactive power transfer. Active power curtailment is now limited to around 1 MWh. Thus the amount of transferred energy can be increased from 5656

MWh to 5804 MWh.

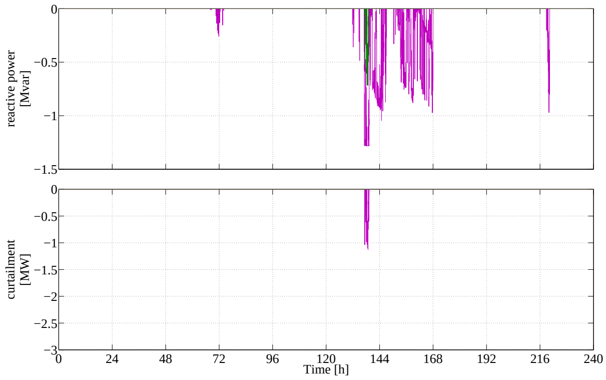

Figure 6 Reactive power consumption and active power curtailment from all wind turbines at the corresponding network nodes in the test system if a coordinated control of both the AVC setpoint and the DG units are used to keep the voltage within the limits.

The variation of the AVR relay set point increases the number of tap changer operation of the OLTC at the substation. As shown in Figure **7** the number of tap operations caused by the set point variation is still as low as seven.

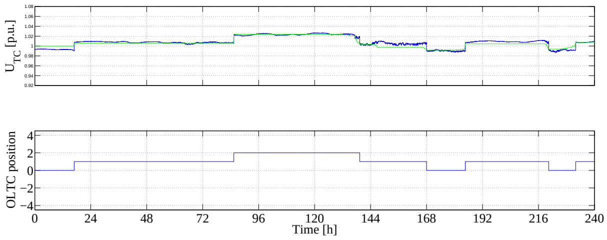

Figure 7 Voltage set point of the AVR relay (upper figure, green line) and the voltage at the substation busbar (upper figure, blue line). The lower figure shows the position of the OLTC.

The key values obtained by the simulations of the local DG control and the coordinated voltage control in a medium voltage network with large DG penetration are summarized in Table 1.

CONCLUSIONS

In distribution networks with a large DG penetration the power flow is not necessarily unidirectional from the substation out in the feeders to the customers. Therefore some assumptions, which were accurate before, can not be presumed under all conditions. In case of a high DG share in medium voltage distribution networks, the voltage is not necessarily decreasing from the substation along the feeder to the customers. Hence, the traditional configuration of the AVC relay with a constant voltage set point is no longer the most beneficial solution, when the DG hosting capacity should be increased.

Table 1 Key values of the simulation of local DG control and coordinated voltage control during ten days in a medium voltage network with a large penetration of DG.

	Local DG Control	Coordinated Voltage Control
Curtailed active power [MWh]	146	1
Network losses [MWh]	66	77
Tap changer operations	1	7
Transferred active power [MWh]	5659	5804

In this paper a voltage control algorithm for coordinated voltage control was proposed. Voltage measurements at the customer side are used to determine the voltage set point of the AVR relay as well as the reactive and active power set point of the DG units.

The proposed control algorithm was used in a case study of an existing medium voltage network. Recorded load and generation data from the actual network over a time period of ten days were used to perform the simulations.

By the use of coordinated voltage control the DG capacity in the case study network could be increased from 13 MW to 38 MW. Active power curtailment was hardly needed to keep the voltage within the limits.

It can be concluded that there is a considerable benefit from using coordinated voltage control in medium voltage networks with high DG penetration.

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