COST-EFFICIENT INTEGRATION OF DISPERSED GENERATION USING VOLTAGE DEPENDENT REACTIVE POWER CONTROL

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ABSTRACT

The increasing extent of dispersed generation in the medium and low voltage grids leads to high investments into the grid. The necessity for network upgrading, especially in wide-spread rural grids with a significant share of overhead lines, is triggered by the customers' requirements concerning grid voltage. In Germany, these requirements are defined by the BDEW guidelines for the connection of distributed generation to the low and medium voltage grid. In its latest version dated June 2008 and applicable since January 2009, these guidelines give the grid operator the possibility to define a reactive power set point depending on the active power generated or on the voltage at the connection point. This report shows how the voltage dependent reactive power control Q(U) extends the grid's capacity for widely dispersed generation, and offers a higher flexibility when assigning the connection point within the grid stabilizing the grid voltage. In addition, network losses are reduced for most operational situations.

INTRODUCTION

For more than 10 years the Renewable Energy Sources Act EEG in Germany has been promoting dispersed generation based on renewable resources. This on-going development is flooding the medium and low voltage grids with generation and leads to high investments into the distribution grids.

Grid upgrading in rural grids dominated by overhead lines typically is motivated by the necessity to keep the voltage at the customer connection points within the low voltage grid between the permissible limits of +/- 10 %. Line and transformer overloading is found in rare cases only.

Reactive power control would be an option to influence the grid voltage, but this degree of freedom has not been used in the past. Generation units connected to the grid typically have to feed into the grid with a power factor close to cosφ = 1, thus avoiding any reactive power flow. The Connection conditions in Germany are defined by the BDEW guidelines published by the grid operators' association. In its latest version dated June 2008 and applicable since January 2009, the guidelines for the connection of generation units to the medium voltage grids define a set of standard schemes for the local control of reactive power. Nearly all technical concepts for dispersed generation including electronic converter solutions allow the presetting of a reactive power value.

One of control schemes defined controls the reactive power in dependence of the grid voltage Q(U). The reactive power flow at the connection point of a generation unit is proportional to the difference between the grid voltage and an adjustable voltage reference value (see Figure 2).

This paper compares the effect of four reactive power control schemes (cosφ = 1, under-excited operation, Q(P) and Q(U)) under the aspects of operation cost (losses) and necessity for investments to reinforce the grid.

REACTIVE POWER AND GRID VOLTAGE

Fundamental Effect

The fundamental effect of a reactive power in-feed or consumption connected to a load in a distribution grid is shown in Figure 1.

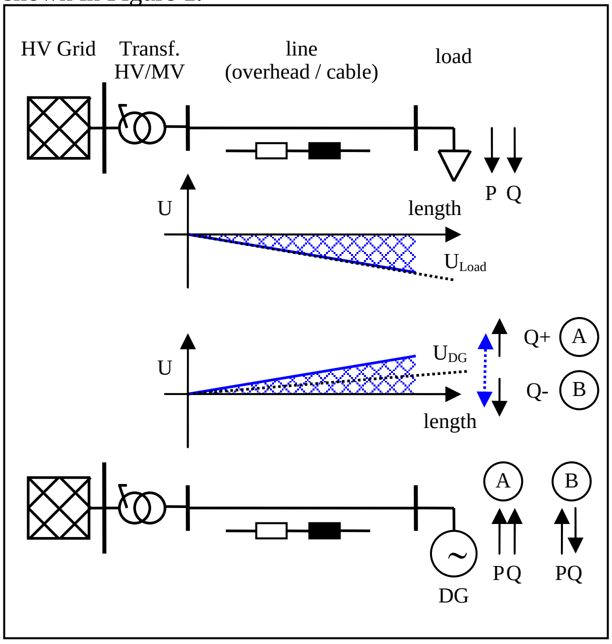

Figure 1: Effect of load flow on grid voltage

A load typically absorbs both active and reactive power. The transfer of this active and re-active power from the transformer substation as the connection point between the distribution grid and the next higher voltage level and the point of connection of the load leads to a reduction of the voltage at the connection point of the load, compared to the voltage at the transformer substation (see Figure 1, above). In analogy the in-feed of active and reactive power leads to an increase in the voltage at the connection point (see Figure 1, below). If this degree of freedom is used during grid operation, the voltage increase caused by active power in-feed (A) can be partly or completely compensated by absorption of reactive power (B). This is very effective above all in overhead lines, as it depends on the inductance of the line impedance.

Standard concepts for Reactive Power Control

The present German guidelines for the technical integration of DG into the MV grid [4] describe several concepts for reactive power control:

- Control of the load factor depending on the active power production cosφ(P),
- Control of the reactive power depending on the voltage at the connection point of a dispersed generation Q(U).

The limitation of the reactive power corresponding to a load factor of minimum 0.95 min assures that there are no inadequate effects on the efficiency of the DG electronic converter.

The scheme cosφ(P) is insensitive to the actual voltage situation in the grid. It thus compensates the voltage effect of the DG unit even if it would be useful for stabilizing the grid voltage. As opposed to that the control Q(U) adapts the reactive power balance according to the grid requirements. Based on these qualitative considerations the quantitative effect of both concepts is compared in the following.

Standardized description of a control Q(U)

The template for the characteristic Q(U) in the guidelines for the MV grid connection of DG is the description in the respective guidelines for the high voltage grid [5]. Based on this, Figure 2 shows the standardized description of this characteristic. The simulations described have been performed in the year 2009. Meanwhile further important milestones could be reached. In cooperation with a manufacturer of PV converters a pilot implementation of the control Q(U) could be set into service in a low voltage PV installation of around 20 kW in the South-West of Germany. Further simulations have been performed with real converters in a LV grid model at FH Wilhelmshaven.

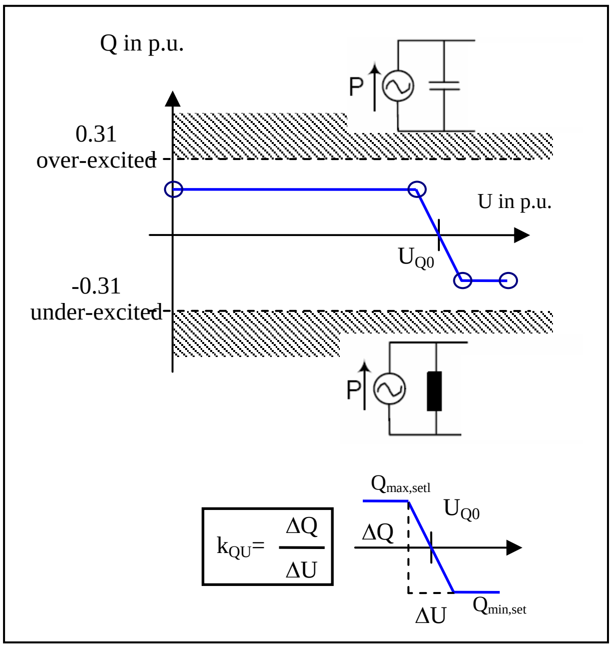

Figure 2: Control Scheme Q(U) as defined in the Connection Guidelines [1].

Criteria for Rective power control

Criteria for an efficient reactive power control can be defined as follows :

- Voltage stabilization
  - Voltage increase in case of low grid voltage, e.g. high load in the grid;
  - Voltage reduction in case of high grid voltage, e.g. high in-feed during low consumption;
- Overall reduction of the grid losses, due to the local production of reactive power during most situations;
- Avoidance of extreme reactive power flows at the connections to the overlaid or to the parallel grids;
- Avoidance of inadmissible interactions between generation units installed in vicinity. Similarly also undesired interactions with the voltage control of the grid (transformer tap control) should be excluded.

Three of the standard schemes control the reactive power independent of the voltage in the grid. Only the scheme Q(U) controls the reactive power depending on the actual grid situation and thus stabilizes the grid voltage.

Table 1 evaluates the behaviour of the control scheme for characteristic grid situations. During low generation and low grid load (A) the voltage cannot be affected, as reactive power is only available as long as active power power is generated (minimum load factor cosφ of 0.95). The same applies to situation B (high load, along with minimum generation).

When high generation coincides with low load (C) all characteristics react in a beneficial way and reduce the voltage increase caused by the dispersed generation.

When high load and high generation occur at the same time (D) the limits of the non-sensitive control schemes are reached. They reduce the grid voltage by additional reactive power consumption, although the grid voltage already is suffering from the reactive power consumption of the loads. The additional reactive power absorbed by the generation units increases the reactive power balance to the HV grid. Only the control scheme Q(ΔU) acts in an optimum way and adapts the reactive power balance to the actual grid situation. This stabilizes the grid voltage and locally generates reactive power that is needed by the loads.

The control scheme cosφ(P) (control of reactive power dependent on the active power generation) reduces the described advantages during low-power situations. The general problem, the non-consideration of the actual grid situation, remains.

SIMULATIONS

To evaluate the quantitative results of an application of Q(U) in the grid, simulations using real MV grids have been performed. These simulations were performed during a diploma thesis, as a cooperation between The institute for electric energy systems and high voltage technology at the University of Karlsruhe (TH) and the Technical Asset Management of EnBW Regional AG [7].

Steady-state Simulations

For the reactive power control the different cases shown in Table 2 are compared. The simulations are performed with the software DIgSILENT PowerFactory. This software offers a programming language to model the reactive power control according to the different control schemes.

Table 1: Schemes Q including set parameters

Symbol	Control Q	Comment
Q=0	./.	Generation with cosφ=1 (pure active power)
Q(du)16	Q(U) with k_{QU}=16 and $(\cos\varphi)_{min}$=0,9	The reactive power possible for cosφ =0.90 is fed in/absorbed for a minimum voltage difference of 2.7% and 0,9% respectively
Q(du)48	Q(U) with k_{QU}=48 and $(\cos\varphi)_{min}$=0,9	
cosPhi0,95	cosφ = 0.95 (under-excited)	Reactive power absorption for voltage reductioon
cosPhi0,90	cosφ = 0.90 (under-excited)	

Model grid

To compare the different behaviours of the control schemes the model grid shown in Figure 4. It consists of a 110-kV-/20-kV transformer substation, with a 20-kV overhead line ring connected. The ring is operated radially, each half-ring contains 15 substations, with a distance of 1 km each. The thermal rated current for overhead line is 319 A, equivaling 11.1 MVA at 20 kV. Thus the ring load may add up to 10.5 MW (at cosφ=0.95), divided up to 30 substations at 350 kW each.

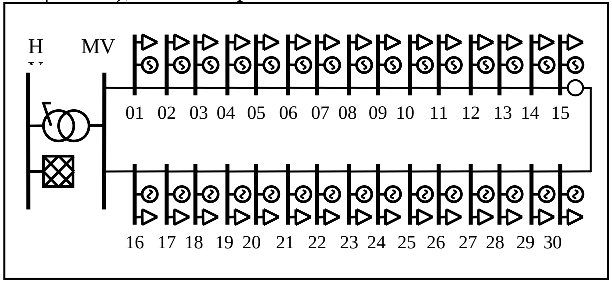

Figure 3: Generic Model Grid

The idea of the simulation is to find out, how much generation power can be connected to the ring without running into voltage band violations. The generated power is distributed evenly among all loads, just like the loads. The generated power is indicated relative to the load, that means a power of 1.0 equals a generation power of 350 kW at each node.

The distribution of the node voltages is visualized for the normal topology as well as for the reconfiguration after the worst-case (n-1) contingency.

Figure 5 and Figure 6 show the grid without generation with a load factor of 1, which meahs 100% of the grid load, for normal operation and the worst-case (n-1) contingency.

The set value of the voltage of the MV grid is defined as 107%, the minimum voltage of 85% in the (n-1) contingency is just reached. The modeled grid load thus equals the maximum admissible grid load. Figure 7 and Figure 8 show the same grid situations, however with minimum load and maximum generation. For the normal topology the grid voltages are within the admissible bandwith independent of the Reactive power control scheme. For the worst-case (n-1) contingency the voltage increase adds up to 115% for the scheme (Q=0). A reduction by the HV/MV transformer tap control is compulsory. As opposed to this situation, the fix schemes (cosφ=0.9; cosφ=0.95) do not lead to any inadmissible node voltages. The same applies to the control Q(U). During normal operation, this case will be seldom. It is much more probable that generation overlaps with a certain grid load.

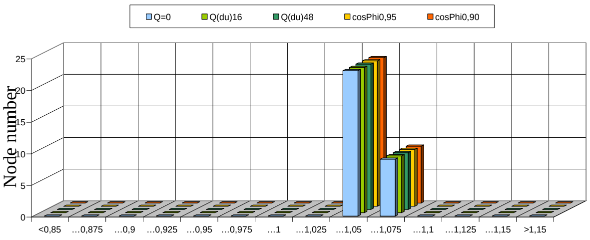

Figure 4: Normal topology, load 1 p.u., generation 0

As an extreme case, the effect of a maximum generation along with a maximum grid load is simulated.

Figure 9 shows the node voltages for normal topology, Figure 10 shows the same situation for the (n-1) contingency. For control schemes that do not of consider the grid voltage both load and generation absorb reactive power.

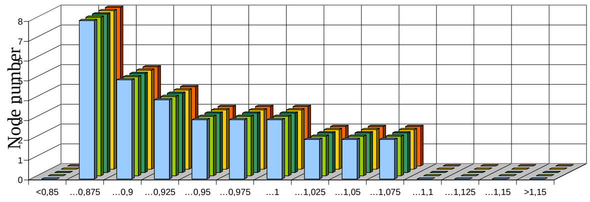

Figure 5: (n-1) contingency, load 1 p.u., generation 0

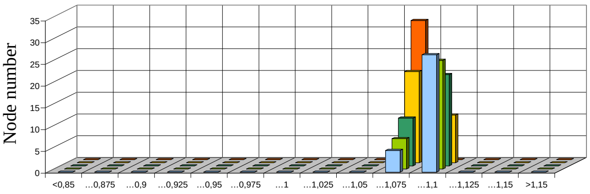

Figure 6: Normal topology, load 0,3 p.u., generation 1 p.u.

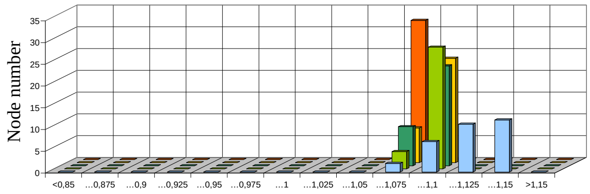

Figure 7: (n-1) contingency, load 0.3 p.u., generation 1 p.u.

For normal operation this has no relevant effect on the voltage. For the (n-1) contingency the increase in the load is obvious. The scheme Q(U) stabilizes the grid voltage. At the same time the local reactive power generation reduces the grid losses. This effect will be even more visible for the simulation of the real grid, shown in the next section.

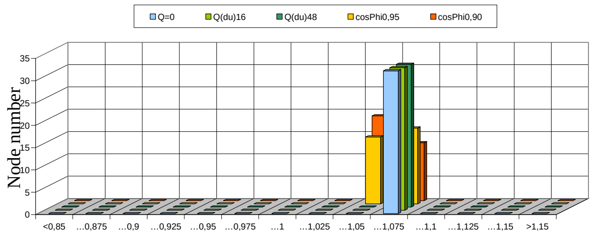

Figure 8: Normal topology, load 0,3 p.u., generation 1 p.u.

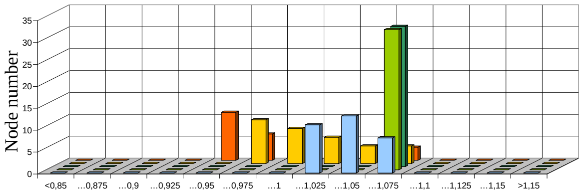

Figure 9: (n-1) contingency, load 0.3 p.u., generation 1 p.u.

Simulation using a real grid

The reactive power control scheme has an influence on both the grid losses as well as on the overall reactive power balance at the connection to the HV grid. These effects will be analyzed in the following based on a real 20-kV grid with two 0.4-kV grids modelled in detail. The 20-kV grid covers a rural region, partly in vicinity to an urban agglomeration. Today the grid connects only few generation units. To increase the generation load, the following procedure is applied:

- All load nodes are equiped with generation units of equal power. The sum power equals the grid load. This means, that the load distribution is real, the generation distribution is homogeneous. Like for the generic grid, a generation level of 1 p.u. means the same nominal power for the generation as for the loads.
- The combinations of different load and generation levels represent a realistic yearly distribution.

The calculation of the yearly losses is done by adding up the losses for each representative scenario of load level and generation level, weighted with the number of hours per year during which this scenario can be expected.

The described procedure is the so-called case 1. Case 2 assumes twice the generation peak power of case 1, with the similar homogeneous distribution in the grid.

The results of the calculations are shown in Figure 11, with a result value given relative to the results for (Q=0). In case 1 the adaptive reactive power control Q(U) leads to slightly reduced grid losses than the reference case (Q=0). The permanent reactive power absorption for the voltage independent control schemes leads to an increase of the losses by 30% up to 60%.

In case 2 all schemes lead to increasing grid losses. It has to be considered however, that without any reactive power control significant grid upgrade investments have to be taken to avoid inadmissible voltage variations. By implementing reactive power control network reinforcement can be avoided in nearly any cases.

The advantage of voltage dependent reactive power control is also obvious when considering the reactive power balance at the HV/MV grid connection (see Figure 12). Positive values mean reactive power absorption, negative values mean reactive power in-feed. For reactive power control schemes insensitive to grid voltage lead to a significant reactive power absorption of the MV grid, which must be considered inadmissible even for case 1.

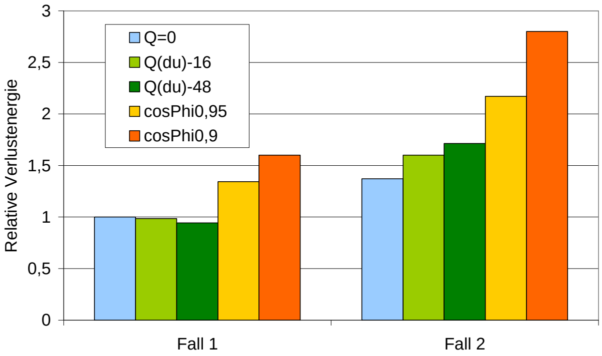

Figure 10: Comparison of the yearly cost of losses

A side-effect of control Q(U) is that the reactive power balance of a MV grid can be easily influenced by the setting of the HV/MV transformer tap. Thus the MV grid can contribute to the reactive power control of the HV and the EHV grid. This presently is investigated in a research activity at EnBW Regional AG.

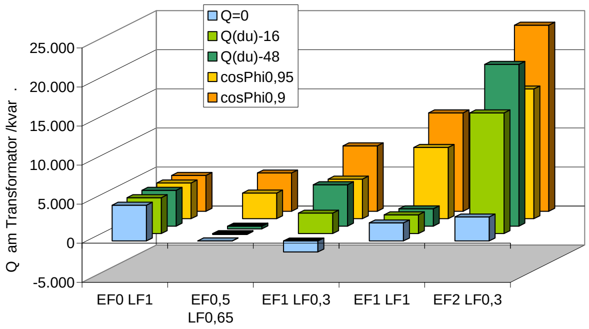

Figure 11: Reactive power balance at the HV/MV connection

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