

IMPROVED GRID INTEGRATION OF DISTRIBUTED GENERATION IN EXISTING NETWORK STRUCTURES

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ABSTRACT

Caused by rapidly increasing numbers as well as installed power of distributed generation especially in rural areas in many cases distribution grids are already close to their limit of grid integration capacity. A highly cost-efficient and short-term implementable methodology to improve grid integration capacity for distributed generation is given by enhanced transformer control concepts. The operating range, technical potentials and the economic efficiency compared to conventional network reinforcement such as installation of additional lines or cables are determined and evaluated by a voltage-level overarching probabilistic approach.

INTRODUCTION

Primarily driven by the Renewable Energy Sources Act (EEG) [1] the development of distributed generation (DG) in Germany has been quite impressive. Especially in rural areas, in many cases distribution grids of the low and medium voltage level are already close to their limits of grid integration capacity. Therefore, cost-intensive network reinforcements to strengthen the given network structure by installation of additional lines, cables and/or transformers or by replacing them with higher rated components, respectively, are required increasingly frequent. Besides high investment costs, such project driven network reinforcements may lead to inefficient network structures in the long run, even if embedded in a long-term planning scheme, since the future DG development can hardly be predicted, especially on the required local level for the medium and low voltage distribution networks. Therefore, short-term implementable highly cost-efficient and flexible solutions based on existing network structures are required.

ANALYSIS AND METHODOLOGY

System observability

The demanded flexibility is preferably to be provided by an improved utilisation of the existing network structure using active (controllable) network components, such as HV/MV-transformers, switches or generating plants. Generally optimal control e.g. of tap-changer positions is achievable under complete knowledge of the current system state i.e. full system observability, whereas incomplete knowledge may result in disadvantageous control settings (Figure 1). Today observability in

medium-voltage-grids is commonly limited to the measurement of voltages and currents in the substation. Additional information about the system state may be accessible by additional measurements and/or close to real time state-estimation with corresponding costs. Therefore, the challenge is getting close to optimal control with minimal information about the current system state, corresponding to point A in Figure 1.

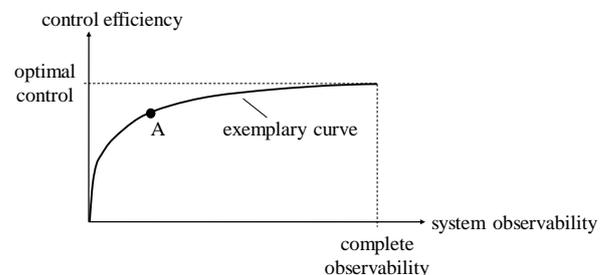


Figure 1 Qualitative discussion of the interrelation between system observability and control efficiency

Transformer control concepts

Since there are no additional network components required, an easily implemented and therefore cost-efficient method for grid integration of DG is improving the transformer control concept of the HV/MV-transformer, which is typically an on-load tap changing transformer controlling the voltage at the low-voltage terminal. In general, the transformer control concept consists of the control variable, a reference variable and the control algorithm. Besides using the voltage at the low-voltage terminal as control variable any other single or even multiple node-voltages are possible, but require enhanced system observability thus additional measurements and telecommunications. The reference value is typically a fixed value slightly higher than the nominal voltage, but may be variable e.g. depending on the actual load situation as well. Determination of the actual load situation is possible by using existing current measurements at the substation, such as the transformer current, which is the summation of all outgoing-circuit currents (*conventional compounding*). In case of distribution grids with DG the estimation of the load situation by using only this single aggregated value is limited because of the summation of load and feed-in currents. Therefore, a more precise estimation is achievable by considering additional information about the actual load situation respectively the system state

given by the measurement of the outgoing-circuit currents (*improved compounding*).

Technical restrictions

Among the criterion for assessment of grid connection of DG given in the relevant technical directives in Germany [2], in practice steady-state voltage stability turns out to be the most critical one, whereby thermal ratings of devices have to be considered as well. The limits for steady-state voltage issues are determined by the European standard EN50160 [3], where a voltage range of about $\pm 10\% U_n$ is given regarding 95% of the 10-minutes mean values of the steady-state node-voltages in medium and low voltage grids. For low voltage grids additionally 100% of the 10-minutes mean values of node-voltages are limited to $U_n + 10\% / -15\% U_n$. Although because of thermal inertia for some grid components, such as cables or transformers a limited short-term overload may be theoretically acceptable, following the relevant technical guidelines distribution grid operators tend to use rated currents for the assessment of grid connection of DG for safety reasons. The complex of grid perturbations by DG such as harmonics or flicker is preferably to be dealt within the generating plants by devices such as filters, short-circuit current limiters etc. and therefore will not be discussed in this paper.

System boundaries

Since the distribution grids of the low and medium voltage level are vertically coupled, especially regarding voltage stability and reactive power, a voltage-level overarching approach was chosen. Because of the voltage regulation at the low voltage terminals of the HV/MV-tap-changing transformers, the distribution grids of low and medium voltage level may be assumed decoupled from the extra-high and high voltage level grids. The resulting system to be considered is marked by the dotted line in Figure 2.

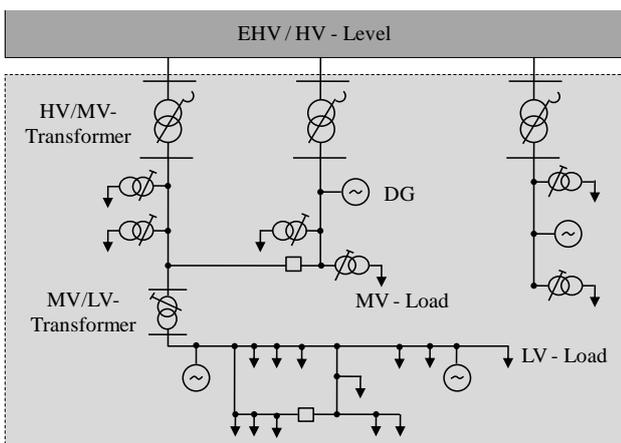


Figure 2 System boundaries

Probabilistic Approach

Because of the stochastically fluctuating feed-in and stochastic load with respect to complex reactive power / voltage-relations as well as voltage dependencies of loads, critical system states cannot be assessed a priori.

Additionally the probability of critical system states may have a significant influence on the cost-efficiency of the grid integration solution, e.g. bilateral agreements on the financial compensation of short-term reduction of power feed-in of DG as a defined option in EEG. Therefore, in this work a probabilistic approach was chosen, which also complies with the requirements in [3]. In a probabilistic approach, the loads and feeders are modelled by distribution functions of their time dependent load characteristics, where interdependencies are considered by correlation factors. Because of the heterogeneity of these distribution functions, analytical methods are not applicable; therefore, a simulative method to calculate the probability of occurrence of critical system states as shown in Figure 3 is required.

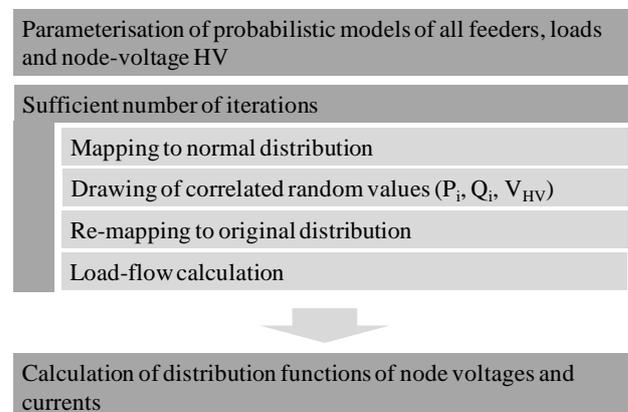


Figure 3 Probabilistic load-flow calculation

RESULTS

To discuss the basic effects of improved transformer control concepts first the voltage range for all nodes in a typical rural ring-operated MV-distribution grid as depicted in Figure 4 and described by Table 1 using different control concepts are compared.



Figure 4 Exemplary rural distribution grid

In each scenario the highest technically admissible wind

power feed-in was connected to the grid at the position marked as DG1 in Figure 4.

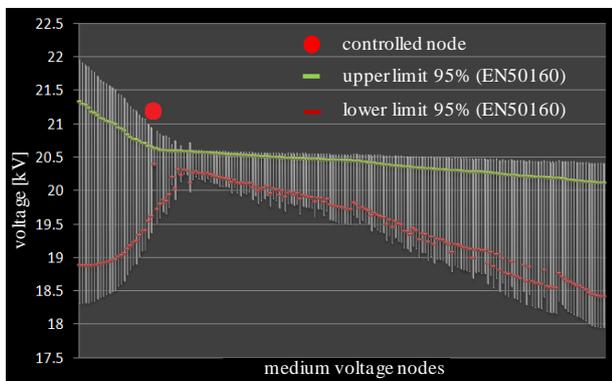
Table 1 Grid characteristics

Area	200 km ²
Peak Load	25.6 MW
Number of stations	216
Average load of station	120 kW
Nominal voltage	20 kV
Load density	0.13 MW / km ²

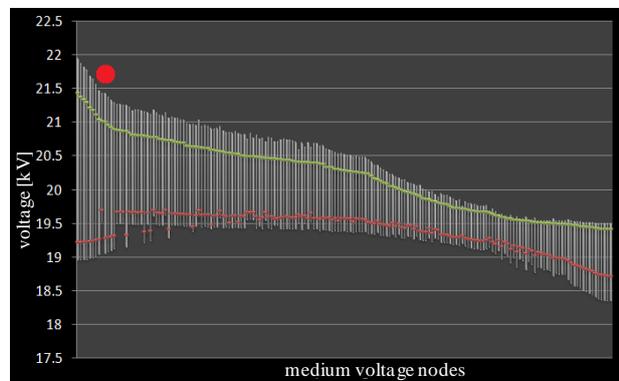
In Figure 5 vertical white lines indicate the voltage range limited by the highest and lowest voltage calculated, each line representing the voltage range at one single grid-node with green and red points representing the highest/lowest value according to the 95%-criterion given in [3]. The lines are arranged according to the highest voltage calculated. In the upper left of Figure 5 the results for today's most common transformer control concept, which is using the *low-voltage terminal* as control variable and a fixed reference variable indicate a highly unbalanced distribution of the voltage ranges, i.e. the voltage at some nodes is controlled very good, the voltage at others rather poor. In general, this concept tends to prefer voltages at nodes electrically close to the substation. Adapting the reference value to the actual load situation according to the control concept of *conventional compounding* results in a significantly

improved admissible installed wind power $P_{DG,inst,max}$ as well as a slightly more balanced distribution of the voltage ranges, as shown in the upper right of Figure 5.

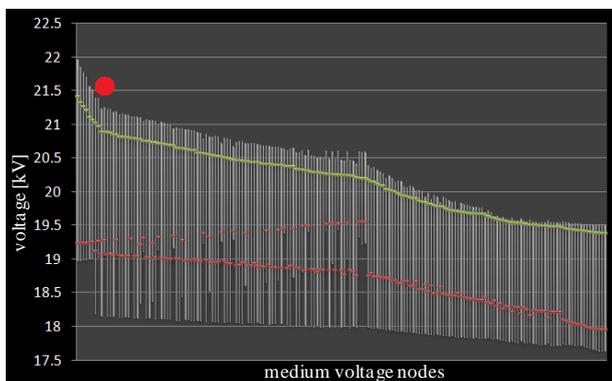
In case of the concept of *improved compounding* (lower left of Figure 5) a further increase of $P_{DG,inst,max}$ up to round about 13 MW is to be stated accompanied by a further equalisation of the resulting voltage ranges. Besides using additional information about the actual load situation i.e. system state in terms of compounding, as mentioned before, the control variable may be changed. For this purpose, an algorithm based on heuristics was developed to determine the optimal control variable (*optimal node*) in a given distribution network. In this scenario the highest increase of $P_{DG,inst,max}$ was achieved, the corresponding voltage ranges are given in the lower right of Figure 5. As the grid capacity for DG is limited only by the most critical network-node an optimisation of $P_{DG,inst,max}$ corresponds to an equalisation of the resulting node-voltage ranges. The potential increase which is achievable by using enhanced transformer control concepts depends on the ratio between the total load $P_{Load,peak}$ in peak-load periods and the highest technically admissible installed power of DG $P_{DG,inst,max}$ as is given in Figure 6. In general, the voltage range consumed by the load determined line voltage drop increases with the load, in the same way the range



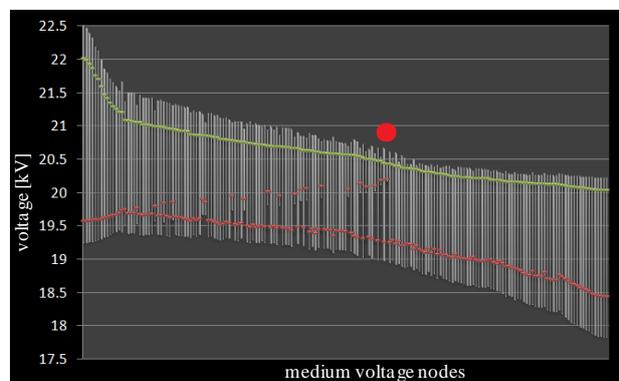
low-voltage terminal; $P_{DG,inst,max}$: 6.56 MW



conventional compounding; $P_{DG,inst,max}$: 9.04 MW



improved compounding; $P_{DG,inst,max}$: 12.96 MW



optimal node; $P_{DG,inst,max}$: 13.6 MW

Figure 5 Maximum admissible installed power of DG and resulting node voltage ranges

available for voltage deviations resulting from grid connection of DG decreases. In an operating range up to a ratio of about $P_{DG,inst,max}/P_{Load,peak} > 1$ Figure 6 shows only small differences of $P_{DG,inst,max}$ between the enhanced control concepts *conventional* and *improved compounding* as well as *optimal node*, whereby a significant improvement compared to the basic *low-voltage terminal* concept is given. In the operating range of ratios $P_{DG,inst,max}/P_{Load,peak} < 1$ in case of *conventional compounding* the maximum installable power of DG decreases rapidly, because the transformer current indicating the actual load situation i.e. system state becomes dominated by load currents, corresponding to a loss of information about the actual DG feed-in.

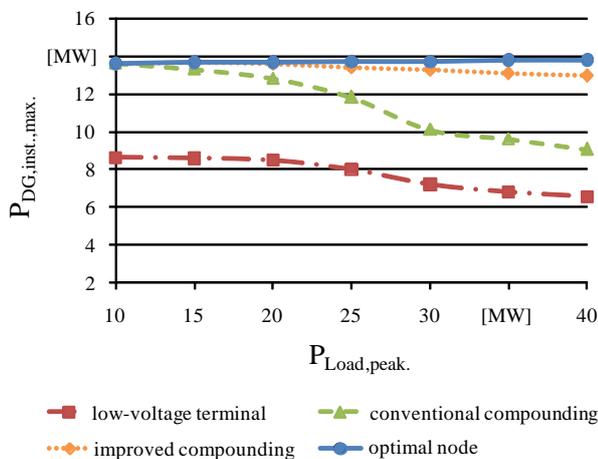


Figure 6 Maximum admissible installed power of DG in dependence of total peak-load

In the next step a second windfarm DG2 is connected to the distribution grid at MV-level as shown in Figure 4. The relation between the maximum technically admissible installed power of DG ($P_{DG1} + P_{DG2}$) depending on the total peak-load given in Figure 7 indicates, that now the difference in terms of $P_{DG,inst,max}$ between *conventional compounding* and *improved compounding* again is negligible for high ratios $P_{DG,inst,max}/P_{Load,peak}$, but remains limited in the complete operating range. Although only one node as control variable is considered the *optimal node* concept provides the highest technical gain in terms of $P_{DG,inst,max}$ again, proving the robustness of this concept.

The economic efficiency is influenced by the investment costs for network reinforcements, additional operating costs as well as network losses, whereby investment and operating costs typically are assumed to be coupled. Compared to structural network reinforcements, such as installation of additional lines, the investment costs of the discussed transformer control concepts are negligible with the exception of the *optimal node* concept, where additional communications are required. Therefore, transformer control concepts are highly cost-effective, if

a technical gain in terms of an increase of $P_{DG,inst,max}$ is achievable, although in case of additional lines the network impedance decreases, resulting in significantly reduced network losses.

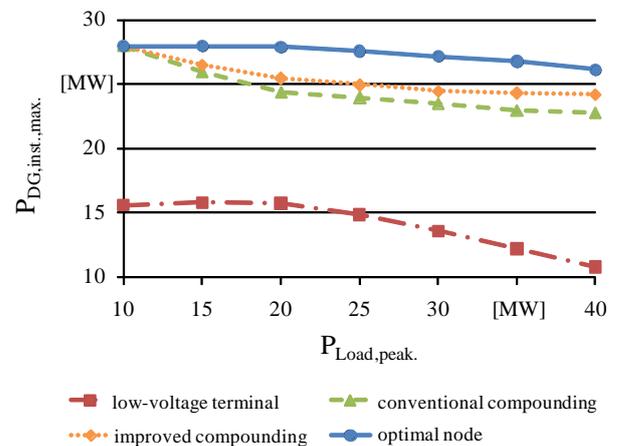


Figure 7 Summarised maximum admissible installed power of DG in dependence of total peak-load

In general, compared to local structural network reinforcements, the tap-changer control influences all node voltages and therefore becomes even more cost-efficient in case of multiple generating plants in different outgoing-circuits.

CONCLUSION

Because of rapid changes in load-structures mainly driven by DG resulting in a highly uncertain prediction of load development as well as high and still increasing numbers and installed capacity of DG connected to distribution networks, short-term implementable highly cost-effective and flexible solutions for grid integration of DG based on existing network structures are required. Using already existing current measurements at substations for the control of tap-changer positions impressive results in terms of increasing the technically admissible installed capacity of DG are achievable almost free of charge. Additionally a control concept based on the determination of optimal control variables was introduced and evaluated.

REFERENCES

- [1] *Renewable Energy Sources Act of 25 October 2008 as last amended by the Act of 11. August 2010*, Federal Law Gazette I p. 2074, Bonn, Germany
- [2] BDEW, 2008, *Generating Plants Connected to Medium Voltage Networks*, Berlin, Germany
- [3] *Voltage characteristics of electricity supplied by public distribution networks*, EN50160:2007