Utilizing fluctuating feed-in characteristics of WEC for grid integration in distribution grids

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1. Introduction

Primarily driven by the Renewable Energy Sources Act as well as the corresponding act on combined heat and power production (CHP) the development of distributed generation and especially wind power in Germany has been quite impressive. Nowadays increasingly more countries are facing similar developments.

Especially in rural areas, in many cases distribution grids of low and medium voltage level are already close to their limits of grid integration capacity. But even in urban and interurban grids grid connection of distributed generation becomes a problem because of overloading issues. Therefore, cost-intensive grid reinforcements to strengthen the given network structure by installation of additional lines and/or transformers or by replacing them with higher rated components, are required increasingly frequent. Besides high investment costs, such single project driven grid reinforcements may lead to in-efficient grid structures in the long run, even if embedded in a long-term planning scheme, since the future distributed generation development can hardly be predicted, especially on the required local level as is needed for the medium and low voltage distribution grids. Therefore highly cost-efficient and flexible solutions are required and should be implemented based on existing grid structures.

There are numerous studies available on the steady-state voltage issue but very few addressing overloading characteristics of grid components with respect to fluctuating feed-in characteristics of distributed generation such as wind farms or PV-plants interacting with conventional power consumers in distribution grids.

2. Analysis

Technical restrictions

Among the criterion for assessment of grid connection of power plants given in the relevant technical directives and standards, in practice steady-state voltage stability and thermal loading capabilities turn out to be the most critical ones. The limits for steady-state voltage issues are determined by the European standard EN50160 [1], where a voltage range of about +/- 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 earth buried cables or transformers a limited short-term over-load 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. Anyway, in this paper these reserves are analyzed and quantified in terms of additional grid connection capability for WECs and other power plants. The complex of grid perturbations by power plants 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, in general a voltage-level overarching approach was chosen. Anyway for complexity reasons the low voltage level was modeled in simplified using grid equivalents consisting of the MV/LV-transformer, an aggregated load model and reserves for voltage drops on lines and transformers in the LV-grid. 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 1.

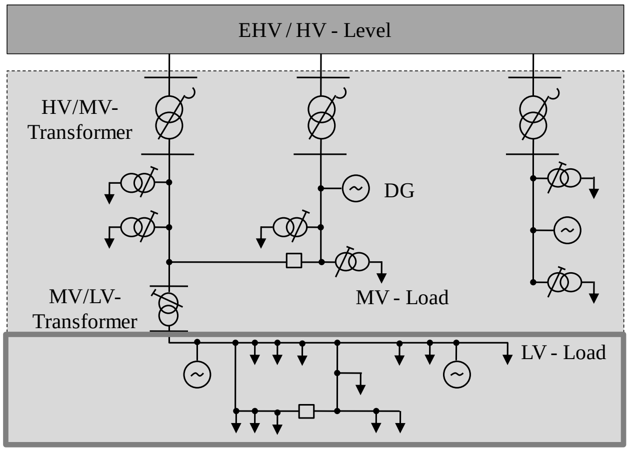

Figure 1: System boundaries

Improved Grid Integration

Conventional grid reinforcements are supposed to strengthen a given network structure by installation of additional lines, cables and/or transformers or by replacing them with higher rated components, respectively. Besides high investment costs, such project driven network reinforcements may lead to inefficient grid structures in the long run, even if embedded in a long-term planning scheme, since the future distributed generation development is hardly predictable, especially on the required local level. Therefore, short-term implementable, cost-efficient and flexible solutions are required.

These demands can be fulfilled by an improved utilization of the existing grid structure using active (controllable) grid components, such as HV/MV-transformers, switches or generating plants. In this paper the focus will be on the reactive power control by power plants as well as on improved transformer control concepts.

In general transformer control concepts consists of a 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 distributed generation 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. 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*). 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 Germany the reactive power feed-in by power plants with grid connection at distribution level is typically given by a fixed power factor, but may also be controlled online by the grid operator. Alternatively characteristics may be applied, either in dependence of the active power output (cosφ(P)) or of the terminal-voltage (Q(V)) as depicted in Figure 2. In Figure 2 V_n is the nominal voltage.

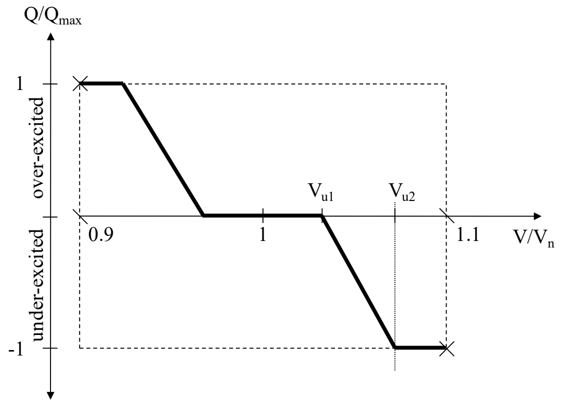

Figure 2: Principle structure Q(V)-characteristic

The reactive power capability of power plants connected to distribution grids typically is required to be equivalent to a power factor of cosφ = $^{+}/_{-}$ 0.95, so with little active power feed-in, the reactive power capability of the power plants is negligible. Therefore the upper left area in Figure 2 is typically of little significance, since low voltage levels in a distribution grid typically corresponds to low active power feed-in of connected distributed generation.

3. Modeling and Approach

Traditionally, the well defined load factor is used to consider the daily load characteristics in the current carrying capacity calculation for grid components such as lines and transformers as shown in Figure 3.

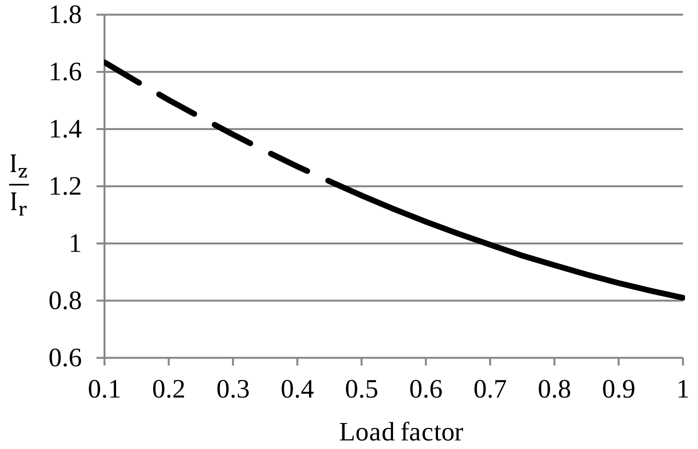

Figure 3: Relation between current carrying capacity and load factor

The current carrying capacity I_z decreases with increasing the underlying load factor. Rated current is usually defined for a load factor of 0.7.

When dealing with fluctuating feed-in characteristics of distributed generation caused by volatile wind speed and solar radiation in fact power flows and corresponding load characteristics on lines and transformers can no longer be described by using traditional load factors such as the common utility load factor (0.7) or even by assuming continuous load (load factor 1.0) appropriately. The fluctuating feed-in characteristics of distributed generation lead to deviating and stochastic load profiles for each time period, but of course there are interdependencies between adjacent time steps. The loading capacity of earth buried lines and all kinds of transformers is determined by thermal boundaries and therefore depending on the load characteristics the grid component is subject to. Besides the superimposition of consumer loads and distributed generation feed-in the effective loading of grid components will be influenced especially by reactive power provision of distributed generation as is often used to address the steady-state voltage issue which comes with grid integration of high amounts of distributed generation. Therefore, such effects have to be considered when determining the loading capability of grid components with respect to grid integration of distributed generation.

Since the loading capability of grid components is highly dependent on the loading conditions before the time step under consideration, load flow calculations are performed for a sequence of one year with discrete time steps of 15 minutes.

Fluctuating feed-in characteristics of distributed generation are considered by generating feed-in time series for each power plant while taking the distance-dependent correlation between feed-ins of each power plant into account. Time series generation is implemented by using second-order Markov chains with state transition matrices obtained from measured time series of PV- and wind power plants as shown in Figure 4.

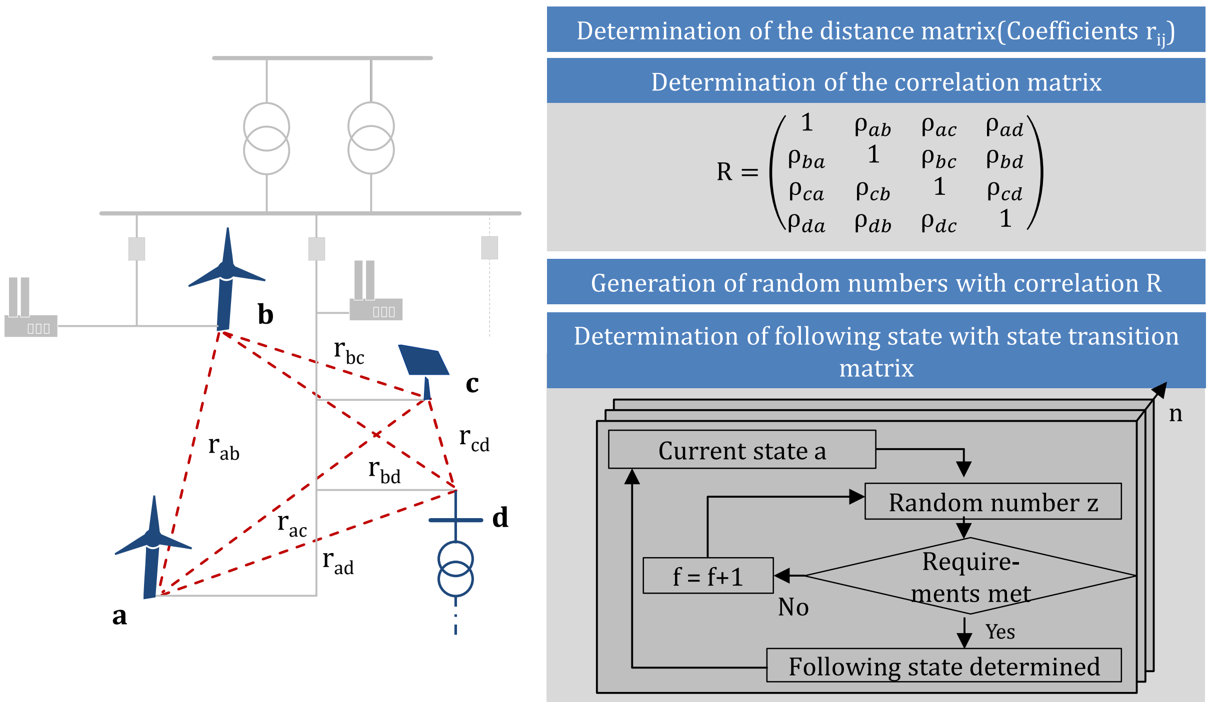

Figure 4: Generation of time series of feed-in and loads in a given distribution grid

Based on the previous power feed-in the following state is determined by using state transition matrices.

The resulting time-dependent loading characteristic of the grid components is divided into different step functions as shown in Figure 5. As steady-state temperatures are not reached after the chosen time step sequence, transient thermal conditions have to be applied. The operation temperature is calculated for each time step by using temperature models for transformers and earth buried lines respectively.

Hence, the thermal step response is determined for each step function separately. The operation temperature for the grid component under consideration is calculated by addition of the individual step responses.

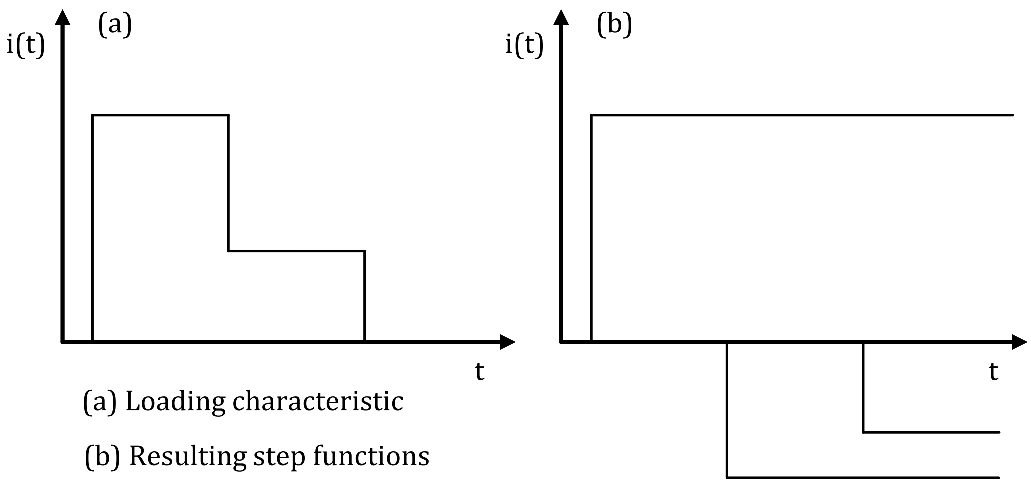

Figure 5: Classification of the loading characteristic into step functions

Due to the random processes in context of the Markov process a Monte Carlo Simulation is used to take the worst case into account and ensure valid grid operation for all possible loading situations.
A schematic overview of the implemented method is shown in Figure 6.
The connected power of distributed generation in the medium voltage level is increased as long as no limits are exceeded to determine the grid integration capacity of distributed generation (DG). Voltage limits are considered as well as thermal limits, depending which limits are more restrictive.
As shown in Figure 6 the grid integration capacity is calculated with two different methods. On the one hand the maximum admissible loading of the grid components is assumed as rated current (benchmark for the developed method). On the other hand the grid integration capacity is calculated with the implemented method under consideration of time-dependent operation temperatures of the grid components.
The benefit of the described method is calculated by comparing the results of the different methods.

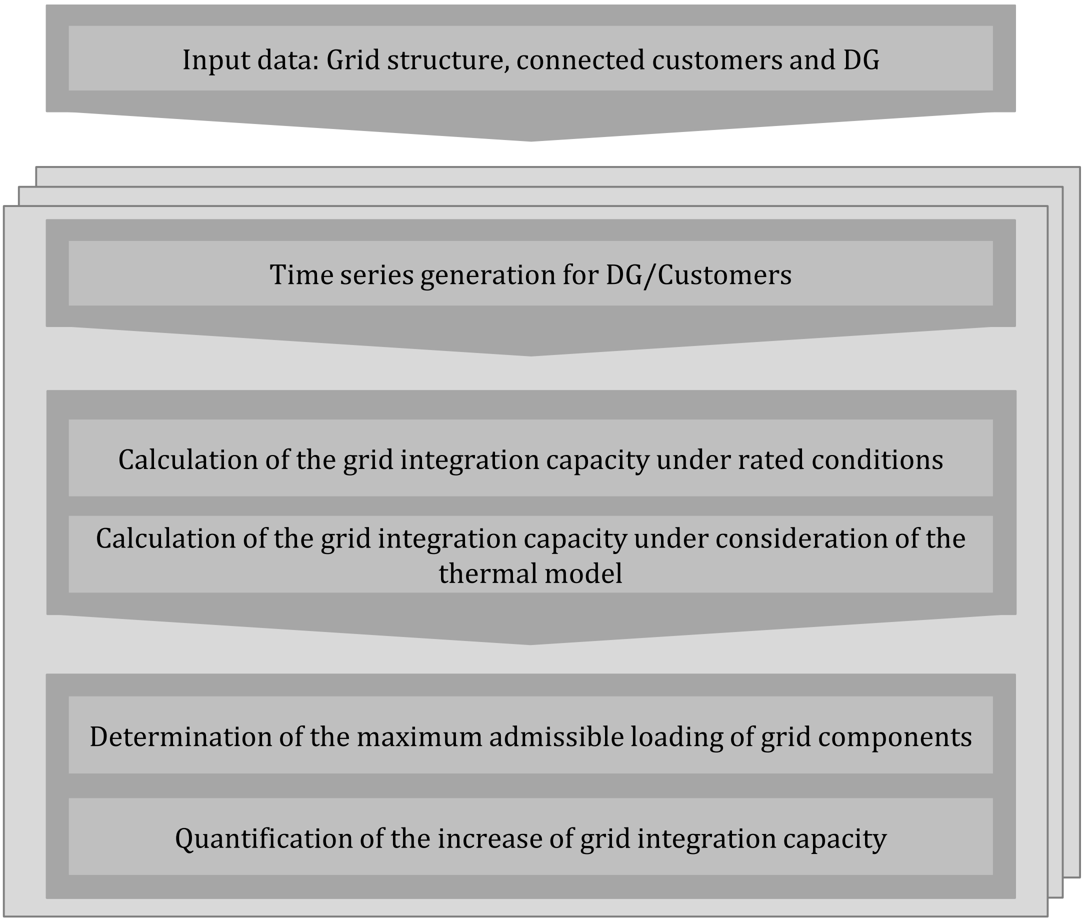

Figure 6: Classification of the loading characteristic into step functions

4. Results

The objective of this paper is to determine the increment of the grid integration capacity under consideration of thermal inertia of earth buried lines and transformers. Therefore, the thermal limit of earth buried lines and transformers is not considered as the rated current, which is defined for a predetermined load factor as mentioned before. In fact, the method takes the time-dependent temperature into account to increase the grid integration capacity as long as the allowed operating temperature of grid components is not exceeded.

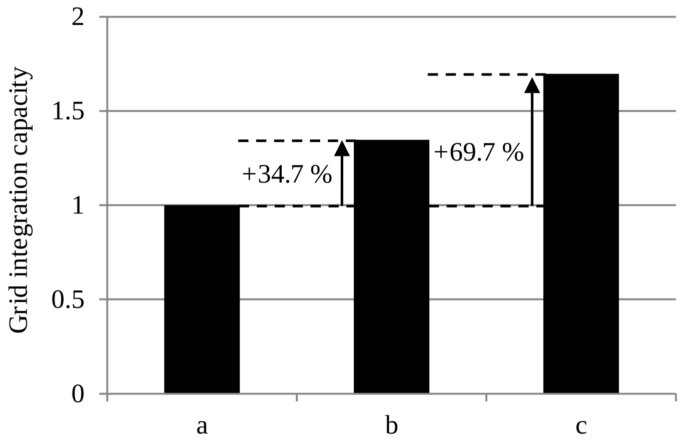

Figure 7: Grid integration capacity based on different underlying methods

A comparison between the grid integration capacities of an exemplary distribution grid based on assumed continuous load (a), the common utility load factor (b) and application of the developed method (c) is given in Figure 7, each related to the grid integration capacity for continuous load (rated current).

As seen in Figure 7, dealing with time series calculations under consideration of thermal inertia of transformers and earth buried lines allows to increase the connected power of distributed generation significantly, since temporary operation above rated conditions is possible.

The increment of the grid integration capacity is highly dependent on the load characteristic the grid component is subject to. Since a large part of the connected power plants in medium voltage grids are wind power plants, grid components often have volatile load characteristics which lead to potentials of increasing the grid integration capacity under consideration of the method described in this paper.

In case of voltage stability issues in the considered distribution grid the benefits of the described method can be achieved in combination with voltage control methods (e.g. reactive power provision by power plants).

5. Conclusion

Investigations based on the described method show that power flows and corresponding load characteristics on lines and transformers can no longer be described by using traditional load factors, since the fluctuating feed-in characteristics of distributed generation such as WECs lead to deviating load profiles for each time sequence. The investigations described in this paper further reveal potentials to increase the connected power of distributed generation when taking advantage of the thermal inertia of earth buried lines and transformers.

Future work contains the investigation of the impact of different ambient conditions, such as grid structure, amount of grid-connected power plants or laying conditions of earth buried lines.