Evaluation of Bottlenecks and Solution Strategies for Integration of Distributed Generation

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Abstract: This paper evaluates the impact of voltage and active power control strategies on the integration of distributed generation into the existing network structures in comparison to the extension of transmission capacity.

Keywords: distribution networks, renewable energy systems, voltage control, optimization, load flow

1. INTRODUCTION

In Germany, distributed generation (DG) from renewable energy sources is fostered by financial subsidies which have led to a dramatic increase of installed photovoltaic capacity from 64 MWp in the year 2000 to 9.800 MWp in 2009 (BMU 2010). Approximately 50 % of the installed capacity is located in the rural areas of Baden-Württemberg and Bavaria (Photon 2010). The increase of DG initiates a paradigm shift in transmission system operation on all voltage levels. Especially the operation of distribution networks faces significant changes due to introduction of (previously virtually non-existent) generating units and the resulting departure from top-down energy transmission.

There are two bottlenecks for the future integration of distributed generation units (DGU): The first restriction is the limited amount of available transmission capacity that, in general, is based on predictions of a slow increase in energy demand, in contrary to the fast pace of the generation capacity addition. The second restriction lies in the maintenance of voltage, particularly in rural areas where the major share of DGUs is installed. The present paper investigates the impact of these bottlenecks on integration of generation from renewable sources into distribution networks and evaluates the potential of control strategies as well as the application of small-scale energy storage devices in comparison to the extension of the transmission capacity.

2. BOTTLENECKS FOR DISTRIBUTED GENERATION

The bottlenecks for integration of DGUs are illustrated for a strongly simplified distribution network that consists of one transmission line, one load at 400 V and two generation units (Fig. 1a).

The first voltage profile (Fig. 1b) demonstrates the current concept of voltage control without a significant amount of DG. The voltage in the feed-in point \(U_t\) is set by the transformer and is usually higher than the nominal voltage in order to reduce energy losses due to transmission and to maintain a voltage reserve for additional load after the voltage drop \(\Delta U_{load}\) (the acceptable voltage margins of \(\pm 10\%\) are defined by the European standard EN 50160). The load-flow is directed from the transformer to the load.

If there is a significant amount of generation capacity in the network, the voltage will not necessarily drop but can also be higher (\(\Delta U_{gen}\)) than the voltage in the feed-in point (Fig. 1c),
which in turn needs to be lowered in order to compensate the voltage increase over the transmission line, especially in situations with simultaneously high energy production and low load. The load-flow direction is inverted.

The bottleneck of transmission capacity limits the additional load-flow that can be caused by DGUs.

The bottleneck of voltage stability becomes obvious, if the same case is considered, while keeping in mind that the energy production is fluctuating (especially in case of renewable energy sources). The combination of peak load and low generation will lead to the same voltage drop \( \Delta U_{\text{load}} \) as shown in Fig. 1b. Since the voltage in the feed-in point \( U_{\text{f}} \) is now lowered, the voltage drop could lead to violation of the lower voltage stability margin (Fig. 1c). Obviously, the requirement for voltage stability margins the installed capacity through the minimum voltage \( U_{\text{th}} \) that is necessary to keep the voltage higher than the lower stability margin in case of peak load and low generation.

### 3. SOLUTION STRATEGIES

Possible solution strategies for the bottlenecks of DG are summarized in Table 1. The state of the art approach is the extension of the transmission capacity through line reinforcement, which also leads to lower voltage drops to some extent resolving the voltage stability bottleneck at the same time. The extension of transmission capacity does not require an introduction of a new control concept or additional automation.

<table>
<thead>
<tr>
<th>Solution Strategy</th>
<th>Effect</th>
<th>Needed Investment</th>
<th>Degree of Automation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) transmission capacity extension</td>
<td>additional transmission capacity for DG and lower voltage drops</td>
<td>line reinforcement</td>
<td>none</td>
</tr>
<tr>
<td>2) local voltage control through reactive power generation</td>
<td>improved voltage quality</td>
<td>payments for the respective system service</td>
<td>low</td>
</tr>
<tr>
<td>3) control of an OLTC based on distributed measurements</td>
<td>improved voltage quality and (to a limited extend) load-flow control</td>
<td>measurement units and unidirectional communication, on-load tap changer</td>
<td>high</td>
</tr>
<tr>
<td>4) global voltage control through reactive power generation</td>
<td>improved voltage quality and (to a limited extend) load-flow control</td>
<td>payments for the respective system service, measurement units, bidirectional communication</td>
<td>very high</td>
</tr>
<tr>
<td>5) global active power control through energy storage</td>
<td>improved voltage quality and load-flow control</td>
<td>payments for the respective system service, measurement units, bidirectional communication, storage devices</td>
<td>very high</td>
</tr>
</tbody>
</table>

The other solution strategies propose a fundamentally different approach – the bottlenecks are resolved by addition of control mechanisms, each of them implying different degrees of automation, devices and costs.
Each evaluation step is based on a scenario that includes a model of a distribution network and load.

For strategies 1 and 5 the DG amount is also part of the scenario. If the maximum possible generation is the goal of the respective evaluation step, the location of the generation units still needs to be defined. In this paper a uniform distribution of installed capacity throughout the network is assumed.

Since only the 20 kV network is considered explicitly, the stability margins are set to $\pm 6\%$ (instead of $\pm 10\%$ according to EN 50160) in order to consider the possibility of additional voltage drop or increase in the 400 V network.

All scenarios represent only one point in time with off-peak load, i.e. worst-case scenarios for DG integration. Energy considerations, as far as they are necessary for estimation of needed storage capacity in strategy 5, are based on extrapolation of the respective worst-case scenario.

### 4.2 Optimization Problem

The calculations of the maximum possible DG (with or without voltage control), the minimum transmission capacity extension as well as the necessary storage capacity are based on a nonlinear constrained optimization problem:

\[
\begin{align*}
\min f(x) \\
g(x) &= b \\
h(x) &\leq c \\
x_l \leq x \leq x_u
\end{align*}
\]

The objective function represents the respective evaluation goal, e.g. to maximize the generation or to minimize transmission capacity. The vector of the optimization variables $x$ contains the variables for real and complex power as well as the phase of current for DGUs and storage devices, the voltages at the nodes, the load flows over the transmission lines and the variables for the extension of the transmission capacity.

The equality constraints $g(x)$ represent the physical model of the distribution network (single phase, AC model) characterized by the energy balance equation

\[
(Y \cdot u) \circ u = S, \quad (2)
\]

where $Y$ is the admittance matrix of the network, $u$ the voltage and $S$ the load at the respective connection point (“$\circ$” represents the Hadamard product). The inequalities stand for voltage and load-flow constraints. Additionally, there are lower and upper bounds for the optimization variables constraining the capacity of storage devices, phase of current etc.

The resulting nonlinear constrained optimization problem is solved numerically with the Ipopt solver (Wächter 2006).

The evaluations based on the optimization problems provide the theoretical potential for integration of DG, minimum transmission capacity extension and minimum storage capacity (as well as the location of devices) with respect to the formulated constraints which represent conditions for safe distribution network operation. At the same time, the optimization problems for the strategies 3, 4 and 5 are equivalent to the respective control problems that are needed to be solved in order to implement the voltage control strategies.

### 5. EVALUATION RESULTS

#### 5.1 Benchmark Distribution Network

The evaluation of the solution strategies are based on a model of a real distribution network (Table 2), which can be considered as a typical example for a radial, rural network in Germany.

| Table 2. Distribution network parameters |
|-------------------|--------------------|
| Peak load active power | 9.38 MW |
| Peak load reactive power | 3.09 MVA |
| Off-peak active power | 4.5 MW |
| Off-peak reactive power | 1.48 MW |
Nominal voltage 20 kV
Voltage in feed-in point 1.04 pu
Max. load-flow through transformer 40 MVA
Number of connection points 248
Number of transmission lines 272

Fig. 3 shows voltage and transmission capacity usage for a peak load scenario without DG and the feed-in voltage of 1.04 pu. The maximum voltage drop amounts to 0.12 pu, the maximum transmission capacity usage is approximately 26 %.

Fig. 4. Off-peak load, maximum DG, current state.

As expected, the voltage increases to 1.06 pu limiting the maximum DG to 12.4 MW. This amounts to 132 % of peak load. Ca. 8.3 MVA is transported to the higher voltage level.

The maximum transmission capacity usage amounts to 22 %, which is even lower than in the previous subsection as load is covered locally by the generation.

5.3 Maximum Possible DG – Voltage Control Strategies

If the voltage at the feed-in point remains at 1.04 pu, the bottleneck is not the transmission capacity but the voltage maintenance. Hence, implementation of voltage control strategies should allow a significant increase of maximum possible DG. The effects of the evaluated voltage control strategies on DG integration are summarized in Table 3.

Table 3. Impact of voltage control on DG integration

<table>
<thead>
<tr>
<th>Solution Strategy</th>
<th>DG Integration</th>
<th>Maximum Usage of Transmission Capacity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2) local voltage control through reactive power generation</td>
<td>19.04</td>
<td>203</td>
</tr>
<tr>
<td>3) control of an OLTC based on distributed measurements</td>
<td>44.6</td>
<td>475</td>
</tr>
<tr>
<td>4) global voltage control through reactive power generation</td>
<td>19.18</td>
<td>204</td>
</tr>
</tbody>
</table>

Local voltage maintenance by DGU (strategy 2) allows a potential of 19.04 MW (or 203 % of peak load, which is equivalent to a 70 % increase in comparison to local voltage control).

Global voltage control (strategy 4) leads to approximately same quantities as the local voltage control. The effect of the global system view is neglectable: The maximum usage of transmission capacity increases only by 1 %.

The highest increase DG potential shows strategy 3, where the voltage in the feed-in point is controlled with respect to actual load and DG. As additional assumption for this evaluation, a lower bound for the voltage in the feed-in point is set to 0.98 pu. The maximum possible DG amounts to 44.6 MW (475 % of peak load) and 38 MVA is transported to the higher voltage level.

With strategy 3 the bottleneck of transmission capacity takes effect, especially for the transmission lines that lead to the feed-in point (Fig. 5). It must be noticed, that the voltage in the feed-in point is 0.98 which is equal to the chosen lower
bound, i.e. the result of the optimization is to set the voltage in the feed-in point as low as possible.

1.1 5.4 Necessary Storage Capacity

In order to evaluate the effect of storage devices the result for maximum possible DG of strategy 3 is taken as fixed input for the optimization in order to find the optimal locations for storage devices and their minimum capacity. Fig. 6 shows the optimized locations of storage devices as numbered circles, the detailed results are summarized in Table 4.

![Fig. 6. Off-peak load, fixed DG of 44.6 MW, storage devices.](image)

**Table 4. Number and Capacity of Storage Devices**

<table>
<thead>
<tr>
<th>Location</th>
<th>No. of Devices</th>
<th>Actual Power Storage [MW]</th>
<th>Extrapolated Capacity for 6 h [MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>10.4</td>
<td>62.4</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>0.17</td>
<td>1.02</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.67</td>
<td>4.02</td>
</tr>
</tbody>
</table>

The optimization results in five storage devices at three different locations. Obviously, storage device 1 is dominant with its actual storage of 10.4 MW. Assuming, that the simulated scenario lasts 6 h, the respective storage device needs a capacity over 60 MWh.

5.5 Necessary Transmission Capacity Extension

As shown in previous subsections, the bottleneck for DG integration is voltage maintenance and not transmission capacity, which only becomes relevant after implementation of strategy 3. In theory, it is still possible to solve the voltage bottleneck problem by line reinforcement. The results are shown in Fig. 7.

![Fig. 7. Off-peak load, fixed DG of 44.6 MW, transmission capacity extension.](image)

The biggest capacity extension amounts to 1200 % (one transmission line needs to be extended by 12 additional transmission lines with the same parameters). As expected, transmission capacity extension is obviously not a practical solution for voltage maintenance.

6. CONCLUSIONS

There are two bottlenecks for integration of DGUs into distribution networks - limited transmission capacity and voltage maintenance. In the present paper the impact of these bottlenecks is evaluated for a real, rural distribution network.

The results show that voltage stability and not transmission capacity is the limiting factor. The maximum possible DG potential is still significantly higher than the peak load, i.e. the energy demand can be covered by generation (if available) within the distribution network.

Five solution strategies are evaluated with respect to the potential of DG integration.

Since the limitation of transmission capacity becomes relevant only after expansion of the voltage stability bottleneck, line reinforcement is a long-term perspective.

Local and global voltage control strategies both allow approximately a 70 % increase of DG potential in comparison to the current state. Global voltage control requires bidirectional communication with online measurement units and DGUs, which leads to high implementation costs. In combination with the lack of additional benefit in comparison to the local voltage control, global voltage control is clearly not a practical solution for increasing DG potential.

A much higher potential (475 % of peak load) is enabled by control of the voltage in the feed-in point. Only unidirectional communication with measurement units is required. In principle, it is even possible to avoid additional online measurements by using an estimator for load and actual DG based on the load-flow through the transformer, weather, standard load profiles and other information about the distribution network. The ratio of additional benefit and costs make voltage control in the feed-in point a practicable solution, especially, if the amount of installed DG capacity is high.

In order to achieve the DG integration of voltage control in the feed-in point with storage devices, a big amount of storage capacity is needed, implying high costs. On the other hand, storage devices allow covering the energy demand,
DG from renewable energy sources is not available, and, in the long term, implementation of advanced operational concepts, which are currently discussed under the label “Smart Grid”.

The evaluation results are based on a distribution network model as well as assumptions about the location of DGUs and, therefore, will vary for other model parameter sets. Nonetheless, the evaluation of bottlenecks and basic effects of the presented solution strategies gives a good indication about necessary measures for increasing DG integration potential: The short-term strategy needs to focus on voltage maintenance by DGUs or control of voltage in the feed-in point, in the long term additional transmission capacity or storage devices can be installed for further DG integration.

REFERENCES


