MAXIMUM PENETRATION LEVEL OF DISTRIBUTED GENERATION WITHOUT VIOLATING VOLTAGE LIMITS

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ABSTRACT

Connection of Distributed Generation (DG) units to a distribution network will result in a local voltage increase. As there will be a maximum on the allowable voltage increase, this will limit the maximum allowable penetration level of DG. By reactive power compensation (by the DG unit itself) a significant increase in allowable penetration level can be achieved. In this paper this and several methods (overrating and generation curtailment) are investigated to achieve a further increase in allowable penetration level.

INTRODUCTION

Connecting Distributed Generation (DG) units to the MV network will cause an increase in voltage. With the increase of DG, it may become difficult to keep the voltage in all feeders within the allowable range in all situations. This will limit the amount of DG that can be connected in a network.

A significant number of papers that discuss the impact of DG units on the voltage profile have been published already (for references, see [1]). Summarizing, most publications conclude that a problem can occur, they determine how large the voltage change will be and they propose solutions to limit the voltage change. It is not determined however, what the maximum allowable penetration level of DG units is, with respect to the voltage change they cause.

The goal of this contribution is to determine the maximum (with respect to the voltage change they cause) allowable penetration level of DG units, assuming that the DG units compensate (a part of) the voltage change they cause. Several techniques to increase the amount of reactive power that the DG unit can compensate are considered and it is investigated how they can be used to increase the maximum penetration level of DG. The paper is restricted to DG units with a power electronic converter.

First some basic theory and methods to increase the maximum allowable penetration level of DG are discussed. The next section then investigates how the maximum allowable penetration can be achieved, assuming that the techniques to increase the penetration level are used. The last two sections present two case studies and a conclusion.

INCREASING PENETRATION LEVEL

This section describes three methods to increase the maximum penetration level. First some theory is given.

Fig. 1. shows a simplified network that is used to give some definitions [1]. The grid is modeled by a voltage source $\underline{V}_s$ and a short-circuit impedance $\underline{Z}_{sc}$. A constant current load and a DG unit are connected to the network. The voltage at their terminals is $\underline{V}_{dg}$. The voltage $\underline{V}_{dg}$ with DG unit disconnected is chosen as the reference voltage. All equations and results in this chapter are in per unit with the short-circuit power S_{sc} = 100 MVA and the supply voltage V_s = 10 kV as the base values (unless otherwise stated).

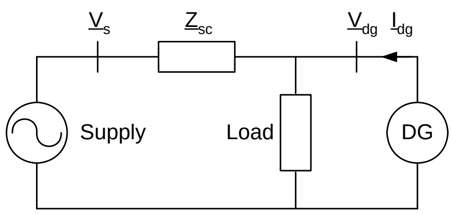


Fig. 1. Network diagram with Thévenin equivalent of grid, load, and DG unit

When the DG unit supplies current to the network the voltage $\underline{V}_{dg}$ will change to $\underline{V}_{dg,new}$. The difference between these two voltages is:

$$\Delta\underline{V}_{dg} = \underline{Z}_{sc}\underline{I}_{dg} \tag{1}$$

Under the assumption that $V_{dg} \cong \underline{V}_s$, the following, very useful, approximation holds [2]:

$$\frac{\Delta V_{dg}}{V_{dg}} \cong \frac{S_{dg}}{S_{sc}} \tag{2}$$

This equation can be used to give a rough indication of the voltage change that will be caused by a DG unit.

Reactive compensation: The first way to increase the maximum penetration level is to use the DG units to absorb reactive power from the grid. In this way the DG units can compensate (a part of) the voltage change they cause. The maximum compensation that can be achieved will be limited by the maximum current of the converter, however. The maximum amount of reactive power that can be consumed is:

$$Q_{dg,\max} = \sqrt{\left(V_{dg} I_{dg,\max}\right)^2 - P_{dg}^2} \tag{3}$$

with the maximal converter current defined as:

$$I_{dg,\max} = \frac{S_{dg,nom}}{V_{dg,nom}} \tag{4}$$

Converter overrating: A possibility to improve the voltage control capability is to increase the maximum current ($I_{dg,max}$) that is allowed for the DG unit converter. Fig. 2a shows for three ratios of X/R how large the overrating of the converter should be to obtain a certain voltage compensation. Fig. 2c shows the overrating for a converter with higher rated power.

Generation curtailment: Another possibility to improve the voltage control capability is to lower the amount of active power that is supplied by the DG unit when the upper voltage limit is exceeded (generation curtailment). As the active current decreases the reactive power can be increased within the maximum current rating of the converter, as can be seen from (3). Fig. 2b and d show how far the active power should be reduced to obtain a certain reduction in voltage. The likelihood of the coincidence of low load and high generation determines the total energy that is lost when curtailment is applied. As the price of electricity is primarily driven by load demand, and curtailment occurs typically during periods of low load, the value of the curtailed energy is likely to be low [3].

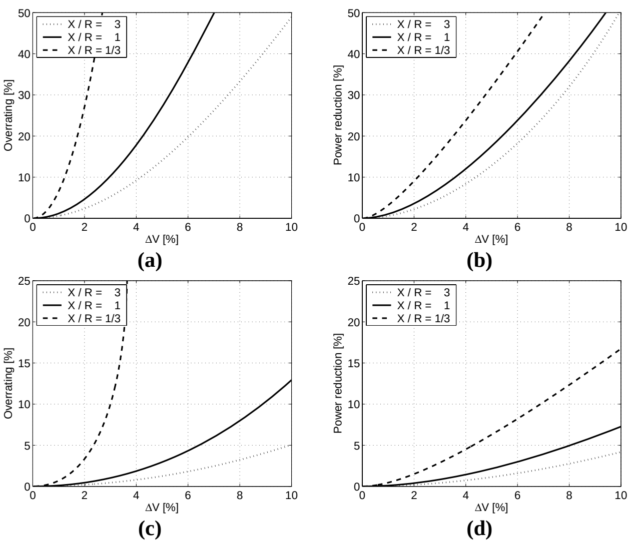


Fig. 2. Measures to improve the voltage control capabilities of converters as a function of the required voltage change: (a) converter overrating ($S_{dg,nom}$ = 0.1 p.u.); (b) active power reduction ($S_{dg,nom}$ = 0.1 p.u.); (c) converter overrating ($S_{dg,nom}$ = 0.4 p.u.); (d) active power reduction ($S_{dg,nom}$ = 0.4 p.u.);

The graphs in Fig. 2 show that the overrating that is needed to obtain a certain voltage change strongly depends on the X/R ratio and the rated power of the converter. The required curtailment is less dependent on the X/R ratio, but it depends strongly on the rated power of the converter. The figure shows further that, especially for converters with a high rated power, only a small percentage of overrating or curtailment is needed to achieve a significant voltage change.

MAXIMUM DG PENETRATION

This chapter will determine how many DG units can be connected to a network when the voltage change caused by the DG units should stay below a certain limit. The DG units are assumed to absorb as much reactive power as possible to limit the voltage increase they cause. The strategies proposed in the previous section are used to achieve a further increase in maximum allowable DG unit penetration. The maximum allowable penetration level will be determined in two steps:

- Firstly the penetration level is determined when the DG units use the maximum possible reactive power to compensate the voltage change they cause.
- Secondly it is investigated how (much) the penetration level can be increased by using overrating and generation curtailment.

DG only

Violation of the voltage limit is most likely to occur in high-generation situations. In that case the DG unit operates at, or close to, its nominal power and the reactive power capability is limited. The active power that is supplied to the grid will result in an increase of V_{dg} due to the voltage drop across the line impedance. As P_{dg} is independent of V_{dg} this results in a decrease of the active current ($P_{dg}=V_{dg}I_{dg}\cos\varphi$) and thus in an increase of the reactive power margin. In this way the converter can undo a part of the voltage increase caused by its active power. First only the margin obtained in this way will be used and the maximum penetration level determined. The voltage change caused by the DG unit active and reactive power can be calculated from:

$$\underline{V}_{dg} = \underline{V}_s + \underline{Z}_{sc} \frac{\underline{S}^*_{dg}}{\underline{V}^*_{dg}} \tag{5}$$

The maximum amount of installed DG unit power ($P_{dg,nom}$) for a particular limit can be calculated by solving (3) – (5) iteratively. The maximum installable DG unit power is shown in Fig. 3 as a function of the maximum voltage change, and for different X/R ratios. The results are obtained for a DG unit that absorbs the maximum available reactive power.

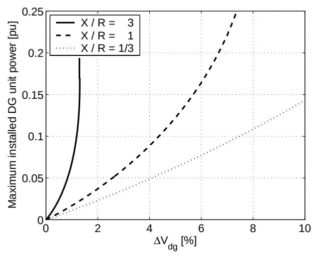
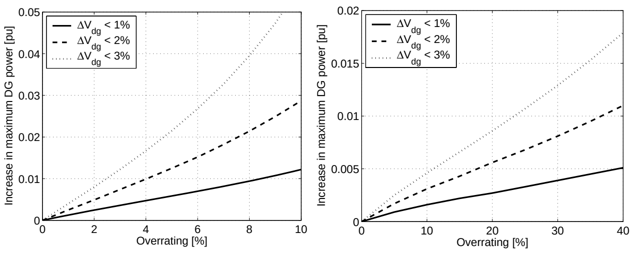


Fig. 3. Maximum installable DG unit power (per unit of short-circuit power) as a function of maximum allowable voltage change for different X/R ratios (V_{dg}=1)

The X/R ratio of the network strongly influences the maximum installable DG unit power. Fig. 3 shows that for an X/R ratio of 3 the voltage change is never larger than ~1.5%. This implies that in this network a large amount of DG can be installed. Also for lower X/R ratios the maximum penetration level can be increased, by absorbing reactive power. According to (2) the DG unit power without compensation is 0.04 p.u. for a 4% voltage change. For example in a network with X/R = 1 the maximum installable DG unit power can be ~ 0.09 p.u. when a 4% voltage change is allowed and the maximum amount of reactive power is absorbed.

Overrating and curtailment

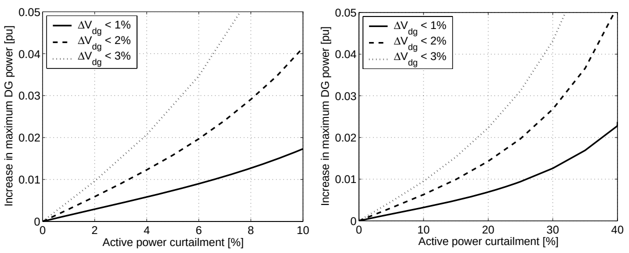
It has been shown in the previous section that the voltage control capability of a DG unit can be improved by converter overrating and generation curtailment. Fig. 4 shows for three different values of the allowed voltage change the maximum installable DG as a function of the converter overrating. The curves are shown for X/R = 1 (Fig. 4a) and for X/R = 1/3 (Fig. 4b). (For X/R = 3 no curves are shown as for this X/R ratio the voltage change is low already, as can be seen from Fig. 3.)



(a) (b)

Fig. 4. Increase in maximum installable DG unit power (per unit of short-circuit power) as a function of converter overrating; (a) X/R = 1; (b) X/R = 1/3; (V_{dg} = 1 p.u.)

The results are obtained by solving (3) - (5) for an increasing overrating of the converter. Comparing the results shows that overrating is much more effective for the higher X/R ratio. For X/R = 1/3 the effect is rather limited.
The increase in installed power that can be achieved with generation curtailment is shown in Fig. 5a and b for an X/R ratio of 1 and 1/3 respectively.



(a) (b)

Fig. 5. Increase in maximum installable DG unit power (per unit of short-circuit power) as a function of active power curtailment; (a) X/R = 1; (b) X/R = 1/3; (V_{dg} = 1p.u.)

Comparing the graphs with Fig. 4 shows that, especially for lower X/R ratios, curtailment is more effective than overrating. Due to the high resistance reducing the active power is very effective.
The values that are obtained from the curves of Fig. 4 and Fig. 5 can be added to the values obtained from Fig. 3. This gives the allowable penetration level when for example a combination of reactive compensation and generation curtailment is applied.

Discussion

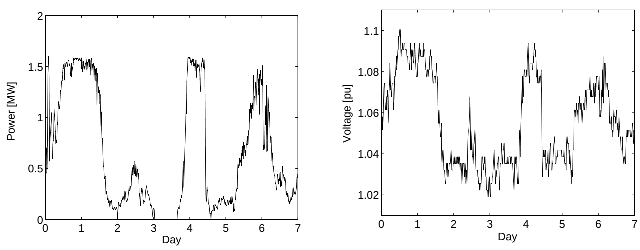
The results in this section show that the maximum allowable DG unit power becomes significantly higher when the DG units absorb reactive power to compensate a part of the voltage change. The allowable penetration level can be increased further by overrating and generation curtailment.
The results are obtained under the assumption that V_{dg} = 10 kV. When it is higher also $Q_{dg,max}$ will be higher. A higher V_{dg} will also affect converter overrating and active power curtailment. For higher voltages a higher penetration level of DG can be allowed.
In this chapter it was assumed that, besides the limitations imposed by the maximum converter current, there are no limitations on the reactive power supplied by the DG units. In reality there might be other limitations, such as for example the maximum current that is allowed in the network, or the minimum power factor that is allowed by grid operators. Other issues that have not been considered, but that can be important are the influence on the losses in the network and the optimal location of the DG units.

CASES

The voltage change that is caused by DG units and the method to increase the maximum allowable penetration levels will be demonstrated for two cases. In these cases it is assumed that the maximum allowable voltage change is 3%.

Case 1

In the first case the influence of a 1.5MW wind turbine connected to a rural, mainly resistive, network with a short-circuit power of ~20MVA and an X/R ratio of ~0.35 is considered. The network has a rather low short-circuit power and the wind turbines cause large voltage fluctuations. This can be seen from Fig. 6, which shows for a period of one week the power supplied by the turbine and the voltage at its terminals.



(a) (b)

Fig. 6. Wind turbine output power (a) and voltage and wind turbine terminals (b)

The effect of the wind turbine on the voltage is determined in a number of steps:

1. The voltage change due to the introduction of one or more DG units can be determined approximately by (2). The short-circuit power at the node to which the wind turbine is connected is 21MVA, with an X/R ratio of 0.35. According to (2) the maximum rated power of the DG unit is 0.6MW when the maximum allowable voltage change is 3%. The wind turbine has a rated power of 1.5MW, implying a maximum voltage change of ~ 7%. This is in compliance with Fig. 6.
2. The change in voltage caused by the wind turbine is thus too large. The proposed solutions to overcome this problem will be considered:
   a. The wind turbine can absorb reactive power. When a maximum voltage change of 3% is allowed, the maximum installable DG unit power can be increased to 0.7MW, as can be determined from Fig. 3. This is only slightly higher than in a case without voltage control. This is, of course, due to the low X/R ratio of the network.
   b. Overrating of the converter will increase its voltage control capability and therefore the maximum amount of power that can be installed. Fig. 4b shows that a 40% overrating of the converter results in a 0.4MW increase in power that can be installed. The total installed powerthat is allowed is then 1.1MW, which is still too low.
   c. Another solution is generation curtailment. Fig 5b shows that 30% curtailment results in 0.8MW increase in active power that can be installed. Adding this to the 0.7MW for a case without control, the total installed DG power is 1.5MW.
3. Generation curtailment shows to be the only option that makes it possible to install the 1.5MW wind turbine without violating the 3% voltage change limit. The highest 30% of the wind turbine power has to be curtailed. For a 1.5MW wind turbine the maximal power that may be supplied is thus 1.05MW. This means a significant reduction in the total energy that is produced. Fig. 6a shows the power output for one week. The total energy produced in this week is ~1100 MWh. When the power is limited to 1.05MW the energy production is ~940 MWh, a reduction of ~15%.

Case 2

In the second case the maximum rated DG unit power that can be connected to a certain node in a MV network. This is done in a number of steps:

1. The short-circuit power at the node is 50MVA, with an X/R ratio of 0.75. According to (2) the rated power of the DG should not be higher than 1.5MW (for a voltage change of 3%).
2. To increase the maximum allowable DG unit penetration level the DG unit can absorb reactive power, possibly in combination with one of the other proposed techniques. The following options to reach a penetration level of 5MW are compared:
   a. By absorbing maximum reactive power an installed power of 0.05p.u. is allowable for a 3% voltage change, as can be seen from Fig. 3. This implies a maximum DG unit power of 2.5MW.
   b. Fig. 4a shows that a 10% overrating of the converter results in an additional increase in power of about 0.05p.u. The total power that can be installed in that case is thus about 5MW.
   c. Fig. 5a shows that for example 8% curtailment results in a 2.5 MW increase in installed power, resulting in a total power of 5MW.

A comparison can be made between the different solutions. The best solution can be defined in different ways. For example the highest annual energy yield or the lowest kWh-price. When the highest annual energy yield has to be obtained, overrating of the converter will be the best solution, as generation curtailment will reduce the annual energy yield. Another possibility is to determine for which option the lowest price per kWh is obtained. It should be calculated how much energy is lost due to curtailment. The revenue loss resulting from it can then be compared by the cost of overrating of the converter.

CONCLUSION

Reactive power compensation significantly increases the maximum allowable penetration level of DG. Especially in networks with a high X/R ratio a significantly higher penetration level of DG can be allowed. For networks with a low X/R ratio generation curtailment (one of the other solutions proposed) offers good possibilities to increase the DG unit penetration level.

The case studies (applied to some typical networks) show that reactive power control by the DG unit can increase the allowable DG power with 15 – 40% already, depending on the X/R ratio. A 10% overrating can increase the allowable penetration level by 50% in networks with an X/R ratio of ~1.8% curtailment was in this network enough to achieve a 100% increase in allowable penetration level.

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