USING STORAGE TO INTEGRATE RENEWABLES INTO THE DISTRIBUTION SYSTEM - A CASE STUDY

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ABSTRACT

In this paper the usage of a storage device to integrate a large amount of wind power into the existing distribution system of EWR is discussed.
In the case study a wind power plant rated at 16 MW is to be connected to the existing distribution system. Normally the plant would be connected via a new cable to the substation, which is roughly 20 km away. In order to reduce the overall cost, EWR decided to find solutions that use only the existing infrastructure.
System impacts such as harmonics, flicker, overloading, and voltage issues have been investigated. Almost all scenarios investigated turned out to have a high impact on the power quality of the distribution system and would be outside the allowed boundaries according to the German medium voltage grid code.
Various solutions have been investigated; one of them is the usage of a storage device. Storage can be used to solve several issues at once, such as reducing the voltage increase during normal operation or reducing the fast voltage drop when shutting the turbines off. Further improvements can be made by reducing the loading on the lines and transformers and thus reducing the losses in the network. A reduction in system impact through flicker can also be achieved.
In the case study it turned out that in order to reduce the system impact to allowed limits according to the German medium voltage grid code, a storage device of 2 MW and an energy capacity of 500 kWh is necessary.

INTRODUCTION

Germany has very ambitious targets in terms of renewable energies (RE). By 2050 80 % of electricity is supposed to be provided by RE [1]. The targets of the state of Rhineland-Palatinate are even more ambitious, according to the coalition agreement of the two governing parties: the target of 100 % RE in the electricity sector is aimed to be reached already by 2030 [2]. These commitments have stimulated the growth of distributed energy sources.
The case study described in this paper is located in the distribution system of EWR Netz GmbH. This distribution system is located southwest of Frankfurt between the cities of Worms, Mainz and Bingen in the state of Rhineland-Palatinate. The network covers 1258 km^2 and comprises 1838 km of 20 kV and 3942 km of 0.4 kV lines. More than 80 % of the lines are cables. The grid is operated normally as an open ring system.
Currently there are more than 5000 photovoltaic systems and 120 wind turbines feeding into the distribution grid of EWR Netz. Already today, the installed capacity exceeds the peak load in the system, leading to a frequent feeding of power from the lower to the higher voltage levels.
In the upcoming ten years the share of RE is likely to triple in the distribution system, mainly through the installation of wind power plants. Figure 1 shows the expected development from 2010 to 2020 of the RE distribution in the system. About half of the predicted capacity will be connected to the 110 kV level, the other half will be integrated in the medium voltage (MV) system.

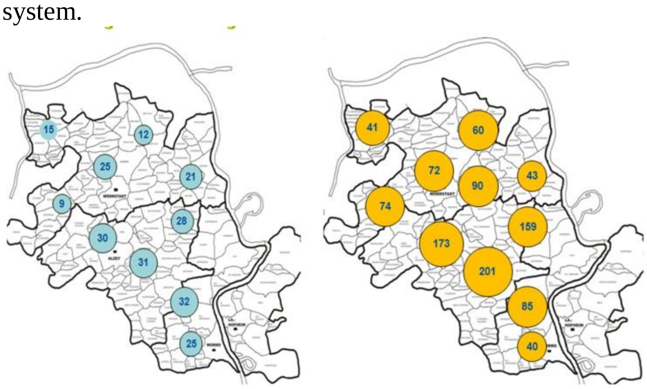

Figure 1 The RE development in the EWR distribution system
left: installed capacity in 2010; right: predicted capacity in 2020 in MW

In the case study the integration of a new wind power plant into the existing MV infrastructure is investigated. The plant comprises five turbines rated to 3.2 MW of the type Repower 3.2M114, so the total installed capacity is thus 16 MW. As the next high voltage substation is approximately 20 km away, a new cable connection would be fairly expensive. Besides the high share of wind power, an additional 3 MW of solar power is currently fed into the distribution system in the same area.
The investigation whether the wind power plant can be connected to the existing medium voltage network and which measures have to be taken has been presented in [3] in detail. A simulation model of the EWR distribution system was developed by Energynautics using DIgSILENT PowerFactory. Based on this, loadflow calculations have been carried out for various load situations, such as low load/high generation and high load/low generation. It turned out that although the loading of the assets such as cables and transformers are within acceptable limits, there are many criteria which go

beyond the limits defined by the German MV grid code [4]. The main issues identified are: slow and fast voltage changes, flicker, harmonics and interharmonics.
In the paper we will describe the possibilities to solve these issues with the help of storage and we will show additional benefits, which could be gained with the installation of an electrical storage system.
In order to get a better understanding, we will explain the results on the basis of a battery storage system with a rating of 1 MVA (up to 2 MVA for short periods) and 500 kWh as it is typically offered to distribution system operators.

RESULTS

In the following chapters the results of the different investigated issues are presented.

Fast Voltage Changes

Fast voltage changes normally result from fast changes in power production due to fluctuating renewables sources such as wind speed or solar irradiation. However, the highest changes can be observed when the complete power plant disconnects at nominal power output from the grid. In order to prevent this fast voltage change, the power output of the system has to be continuously reduced. This can be done by installing an electrical storage system close to the wind power plant.
For our case study, we want to determine the necessary capacity in terms of power rating and energy contents.
The wind power plant will be connected via two cable lines to the substation. On one of the lines 9.6 MW will be connected, on the other one 6.4 MW. Figure 2 gives an overview of the grid topology after the connection of the wind power plant.

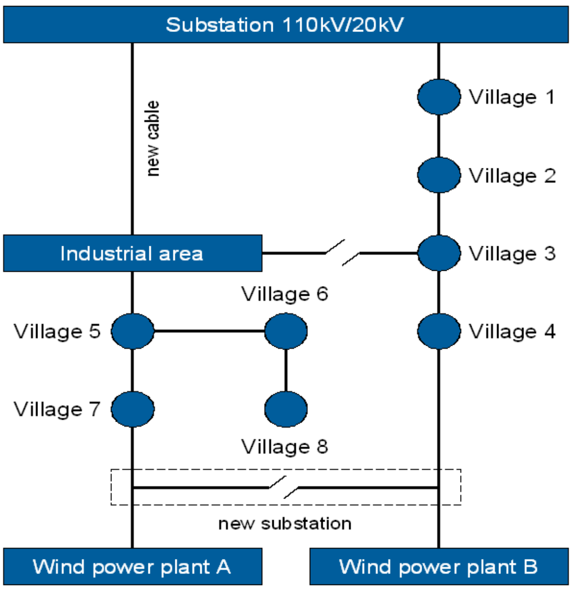

Figure 2: Grid topology after connecting the wind power plant
Rating of plant A: 9.6 MW, rating of plant B: 6.4 MW

The further investigations will be based on the 9.6 MW part of the wind power plant, as this is the more demanding one.
The maximum voltage drop after disconnection has been determined to be -6.28 %. According to the German MV Grid Code only 5 % fast voltage change are allowed.
In order to estimate the necessary power rating of the storage, a linear approximation is carried out.

Poweroutput before disconnection:	9.6 MVA
Poweroutput after disconnection:	0 MVA
Voltage difference:	-6.28 %
Power-voltage gradient: -9.6 MVA/-6.28 % =	1.53 MVA/%
Allowed voltage drop according to German Grid Code:	-5,0 %
Exceeding of limit:	1.28 %
Necessary supporting power: 1.28 % x 1,53 MVA/% =	**1.95 MVA**

In case a reduction of the total power within 1 minute is to be achieved, e.g. to allow some time to let the tap changer of the transformer to act, the installed capacity of the storage has to be 16 kWh.
For this use case, the typical battery storage with up to 2 MVA rating is perfectly suited, however 500 kWh is way more than the necessary 16 kWh and for this purpose it would be oversized.
From this perspective other technologies might be better suited to reduce fast voltage changes. These are, amongst others, superconducting magnetic energy storage (SMES), flywheels and super capacitors. These technologies typically have a high power output and low energy capacity.
In analogy to the disconnection of the wind power plant, the fast voltage change can also be dampened during the connection of the plant.

Slow Voltage Changes and Voltage Limits

According to the German MV grid code, the voltage rise after connecting the wind power plant should not exceed 2 % compared to before. Setting the power factor of the wind power plant to cos $\phi = 1$, load flow calculations show that the limit is exceeded at four MV substations in the system. This is due to the fairly low short circuit power. The option to reduce the voltage by consuming reactive power would lead to additional flows on the lines and thus to an overloading of the cables. According to the German MV grid code, the operation of the wind power plant would not be allowed.
The highest voltage observed amounts to 2.75 %, thus the limit is exceeded by 0.75 % corresponding to a power of

1.15 MVA. With a rating of 500 kWh the given battery storage would be able to charge with this power in best case for only 26 minutes. As wind power plants do operate at nominal power typically for a couple of hours in a row, this energy capacity is far too low.
However, as the main interest of the grid operator is to keep the voltage according to DIN EN 50160 in the range of ±10 % of the nominal voltage, meaning that the voltage is allowed to change (slowly) by considerably higher values then 2 % (in theory up to 20 %). As long as the grid operator has a very good understanding of the voltage profile, the 2 % limit of the German MV grid code is not relevant. In Figure 3 the voltage profile along both feeders is shown during a high wind and low load situation. The voltage in the MV grid has to be kept below 1.07 p.u, in order to allow for a voltage increase of up to 3 % in the LV network.

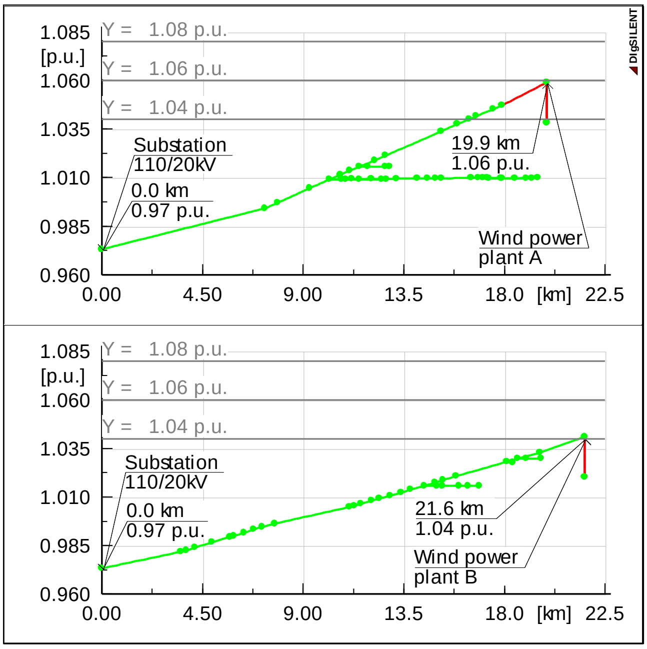

Figure 3: Voltage profile along the MV-feeders for a high wind and low load situation

Possible use cases of storage systems in terms of keeping the steady state voltage limits are given, where only small time periods have to be bridged. For example peak shaving and voltage control with the storage system could be done in order to reduce the number of tap changes of the transformer used for voltage control in the MV system.
In many cases, there are also problems in the low voltage system induced by renewables. Here mainly photovoltaic systems are installed. In case of reversed feeding into the medium voltage grid, a voltage increase in the low voltage system can be observed. This can lead to a violation of the allowed upper voltage limit.
As the maximum possible PV production can be easily calculated and will always appear during midday, storage with a fairly low energy capacity can help to prevent the violation of the upper voltage limit. By charging during midday the voltage in the medium voltage system can be kept low allowing a higher voltage drop in the low voltage system.
With 1 MVA from the battery in the above example the voltage could be reduced by 0.65 %. Assuming that the PV load peak lasts for about one hour during midday and the maximum reduction is only necessary at 12 o'clock, the necessary energy capacity amounts with a linear approximation to $E = 1\,h \cdot 1\,MW \cdot 0.5 = 500\,kWh$. This is exactly the capacity of the given battery, thus a realistic support in terms of keeping the voltage limits can be expected from a storage system.

Flicker

Flicker is voltage fluctuations due to fast load changes. Inverter-based storage systems can compensate for these fast changes in active power and therefore reduce flicker. For this high capacities in terms of energy are not necessary.
Typical voltage changes introduced by wind power plants are in the order of ±1-2 %. To compensate for these, a storage system with a power rating of 1.5 to 3 MW is necessary.
The given battery with its short term power of up to 2 MVA can therefore considerably reduce the flicker level.

Harmonics and Interharmonics

Typically harmonics and interharmonics are created by frequency converters or inverters used in renewable power plants.
In the case study, the wind power plant is connected to a rather weak grid leading to a violation of a number of harmonic and interharmonic limits.
Harmonics can typically not be compensated by the power electronics of a storage system, instead additional harmonics can be inducted into the power system by the inverter of the storage system.
Other solutions have to be found in this case such as the installation of filters.

Cable loading and grid losses

Grid losses in distribution systems are dominated by thermal losses in the cables. These losses increase quadratically with the current on the lines.

$$P_V = R \cdot I^2$$

The feed-in current of the wind power plant (WPP) can be determined through the voltage at the point of common coupling (PCC) and the produced power.

$$I_{WPP} = \frac{P_{WPP}}{U_{PCC}}$$

Under the assumption that the voltage at the PCC is constant, the current is proportional to the power.

$$I_{WPP} \sim P_{WPP}$$

The maximum grid losses can then be considered to be proportional to the square of the nominal power output of the wind power plant.

$$P_V \sim P_{WPP}^2$$

With a storage rated to 10 % of the WPP capacity, the grid will be only loaded with 0.9 P_{WPP}. The losses are then reduced to

$$P_V \sim (0.9 \cdot P_{WPP})^2 = 0.81 \cdot P_{WPP}^2$$

When discharging the storage at a later time at 0.1 P_{WPP} the following additional losses will arise.

$$P_V \sim (0.1 \cdot P_{WPP})^2 = 0.01 \cdot P_{WPP}^2$$

The overall reduced grid losses are then

$$\Delta P_V \sim (1 - 0{,}81 + 0{,}01) P_{WPP}^2$$

Thus grid losses can be reduced by up to 18 %. However as the reduction of power can only be kept up for a short period (approx. 30 minutes) by the storage system, no major advantages in terms of reduction in grid losses and grid loading are expected.

Curtailment

When integrating the wind power plant into the existing distribution grid, the grid will be operated at its thermal limits. However, as a further increase in PV penetration in the EWR distribution grid is expected in the upcoming years, overload situations are likely to happen. According to the German Renewable Energy Law, the wind power plant would have to reduce its power output. In such a case, storage can be used to store the otherwise curtailed energy and release it at a later stage. The described use case in the voltage limits section for shaving the PV peak is also applicable in this case.

In case of a temporarily topology change, e.g. back feeding from another substation due to maintenance work, which will typically last for a couple of days, no great benefits from storage are expected, as the energy capacity is far too low.

CONCLUSIONS

This investigation of the integration of a wind power plant into the medium voltage distribution grid shows that although the loading of the assets such as cables and transformers are within acceptable limits, there are many criteria which go beyond the limits defined by the German MV grid code. These are: slow and fast voltage changes, flicker, harmonics and interharmonics.

Various solutions have been investigated; one of them was the usage of a storage device. Storage can be used to solve several issues at once, such as reducing the voltage increase during normal operation or reducing the fast voltage drop when shutting the turbines off. Furthermore it can reduce the loading on the lines and transformers and thus reduce the losses in the network. A reduction in system impact through flicker can also be achieved. While in theory there are many possible advantages of using storage, today in practice decentralised storage systems such as batteries or flywheels have a rather low energy capacity and are still very expensive. Considering a wind turbine producing power at rated output for several hours to days, the energy capacity of the storage device necessary to safely reduce the power over the whole period is rather large. Therefore only a few issues can realistically be solved by using a storage device today and in the near future. The issues identified here have in common that they are characterized by a short event with high power and low energy need: flicker, fast voltage changes, and peak shaving of photovoltaic during midday. For all other issues other solutions have to be found, such as wide-area voltage control, curtailment, and filtering.

In the case study it turned out that in order to reduce the system impact to allowed limits according to the German medium voltage grid code, a storage device of 2 MW and an energy capacity of 500 kWh is necessary, which corresponds to the typical battery storage system offered to the distribution system operators.

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