

A comparison of wind integration experiences in some high penetration areas

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Abstract—The amount of wind power in the world increases fast. The background for this development is improved technology, decreased costs for the units and an increased concern of the environmental problems of competing technologies such as fossil fuels. The amount of wind power is though not spread equally over the world, so in some areas there is a comparatively high concentration. The aim of this paper is to make an overview of some of these areas and shortly describe the consequences of the increase of wind power. The aim is also to try to draw some generic conclusions, in order to get some estimation about what will happen when the amount of wind power increases for other regions where wind power penetration is expected to reach high values in future.

Index Terms— Wind power, integration, power system, power transmission, balancing of wind power.

I. INTRODUCTION

WINDMILLS have existed for at least three thousand years, mainly for grinding grain or pumping water. The use of windmills to generate electricity is a twentieth-century development and in the early 1970s started the development towards modern wind turbine technology. At the beginning of year 2006, the installed capacity of wind power was about 60 000 MW [1], which corresponds to an energy production of about 120 TWh per year. The increase is related to a fast development of new technology, where new ideas of the electric generation systems have been implemented, the size of the wind power plants has grown, the environmental impact has decreased, and the cost per produced kWh has decreased significantly. One important driving force for the fast growth is also the increasing concern for the environment. The total electric consumption in the world is currently around 17 500 TWh per year [2], which means that around 0.7% of this electricity comes from wind power.

For the future it is important to get a view on how systems with larger shares of wind power can be operated and designed in order to get an efficient integration without violating the system security. In section 2 below system requirements for wind power in an isolated area is treated and in section 3 the method is extended to areas that are interconnected to other areas [3]. An analysis of the different systems is presented in section 4

and section 5 provides a summary and the conclusions.

II. SYSTEM REQUIREMENTS FOR AN ISOLATED REGION WITH SIGNIFICANT AMOUNTS OF WIND POWER

For any power system with or without a large proportion of wind power it is important to operate the system in an efficient way and to have enough margins in order to keep a high reliability. This is a challenging complex task which here will be shortly summarized. We here call the isolated system “region X” and important factors to be considered are:

- Lowest consumption level in X
- Possibilities to control other power sources in X
- Internal grid problems in X

A. Medium penetration of wind power

Fig. 1 shows an example concerning how the consumption and the wind power production could look like in a power system. The data in the figure is from West Denmark in January 2000. In reality Denmark West is highly interconnected to three other countries, but in this section the figure will illustrate the challenge of integrating wind power in an isolated area.

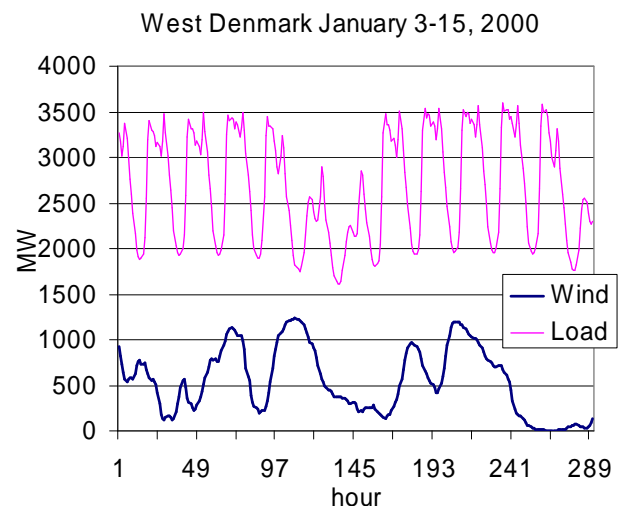


Fig 1. Total consumption and wind power production (20%) for illustration of wind power integration in an isolated power system. (Data source: www.energinet.dk).

In the example in Fig. 1, wind power covers 20% of the consumed energy during the period. The problems that occur can be solved in the following way:

a. There must be enough power plants during times with low wind contribution. At around hour 260, the consumption is high and the wind power production is low. At these situations there must be enough power plants, except for the wind power plants, to meet the load. A further analysis is found in, e.g., reference [4].

b. There must be enough power plants with fast control during high wind situations. In a power system, there must be a continuous balance between production and consumption. The only stored energy, rotational energy in all rotating parts of generators and turbines, is only enough for the operation of the power system for some seconds, and therefore there have to be power plants that balance changes in production and/or consumption. At hour 110, the margin between consumption and production is relatively small. Also at this situation there must be enough power plants that can keep the needed production-consumption system balance when the load and/or wind power production changes. In thermal power systems this means that there must be enough capacity in operating thermal plants and these plants must have margins, both to increase and to decrease the production [5]. During these situations it is also important to have some power plants that could provide a variable reactive power for voltage control.

c. The system must be robust enough to survive a dimensioning fault. In all power systems there can be faults, and it is not acceptable that a single fault, e.g. a short circuit, causes a total collapse of the system. A short circuit can, e.g., cause the voltage in the system to vary significantly, and it is important that the rest of the system can manage this, so a single fault does not cause cascading outages of lines and/or production units.

d. There must be enough reserves covering all possible uncertainties of supply and demand (system net imbalances), for example situations with large decrease of total wind power production. This question is about the same as the one under b, but here the question concerns larger capacities that have to be available within some hours. The largest decreases in wind power do not occur instantaneously, like for conventional plants tripping off. Even during a storm front a (distributed) wind power will take 4..6 hours to fall. This implies maximum ramp rates of 10 MW/min in Western Denmark (2400 MW wind [6]) and 16 MW/min in North Germany (6000 MW installed). Assume that the total amount of wind power decreases as much as during hour 72 in Fig. 1, and that this occurs at the same time as the load increases as in hour 85. During this situation, there must be enough power plants that can increase the production to compensate both for the load increase and for the wind power decrease. The question is though if this is a dimensioning issue and how reliable forecasts are for these situations. More important may be the outage of a power plant with high capacity (the dimensioning fault, c). As for the UCTE-grid it is necessary to consider the outage of the two block units of the power plant with the highest capacity (total 3000

MW) when working on the same bus bar [7].

e. Handling of possible problems in the internal grid. Assume that wind power is located in one part of the region and the main consumption in another part. To be able to use the installed capacity of wind power, there must be enough transmission capacity between the wind power source and the consumption areas.

B. High wind power penetration

Now assume that there is more wind in the system, c.f. Fig. 2.

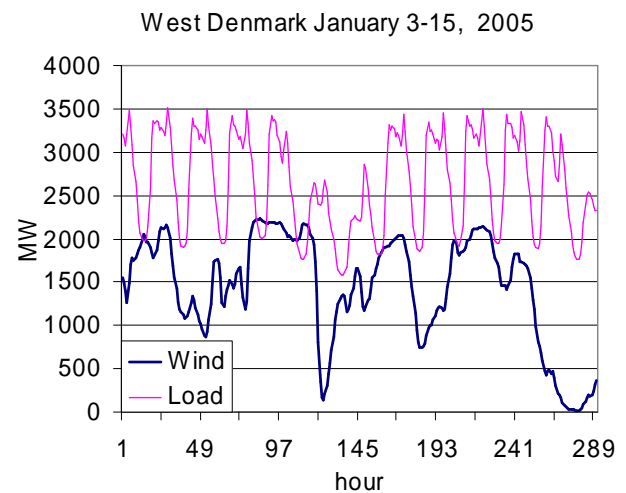


Fig 2. Total consumption and wind power production (55%) for illustration of wind power integration in an isolated power system. The illustrative day of January 8 is here included when a comparatively large part of wind power was shut down because of a storm front. (Data source: www.energinet.dk).

In the example in Fig. 2, wind power covers 55% of the total load during the week. The difference compared to Fig. 1 is that during hour 11, wind power covers the whole load. This leads to a new type of situation that has to be handled.

f. Possibility to regulate down available wind power during low power consumption. When wind power covers the whole load, there is of course still a possibility that the production in the wind power plants will decrease and/or the consumption will increase. This is a specific situation of type b above. Also in this case there must be power plants that can increase the production fast. To make this possible, it is often necessary to decrease wind power in these situations in order to keep thermal power plants on a low production level, so they can increase their production if needed. A method for how to perform this is presented in [8].

Fig 2 also shows some situations when available wind power production is much higher than the load during several hours in the week. In this type of system the system requirements increases:

g. Possibility of continuous control of wind power. The total production in wind power cannot exceed the total load for longer periods. If total wind power exceeds total load, then the consequence will be that the frequency in the system will start to increase. This means that when the frequency increases some wind power plants have be

totally shut down, or several wind power plants have to decrease their production by, e.g., pitch control. One alternative is storage, but currently storage of large amounts of energy is comparatively expensive. In the example in Fig. 2, 0.2% of available wind energy has to be spilled. This means that the available wind power will be 0.2% more expensive, compared to the situation if all wind power could be used.

III. SYSTEM REQUIREMENTS FOR A REGION WITH SIGNIFICANT AMOUNTS OF WIND POWER WHERE THE REGION IS INTERCONNECTED WITH OTHER REGIONS

Now assume that the studied region is connected to other regions. In reality this is the way a power system looks like, including the western Danish system, which was used for illustration purposes in Fig. 1-2. The European system is, e.g., one system with interconnections between nearly all neighboring countries. It is therefore important to consider that wind power variations in, e.g., northern Germany can be balanced in power plants in northern Germany or in neighboring regions. Because of this there are also some additional items that have to be considered concerning system requirements for an efficient and reliable operation. The main question is then the transmission capability between region X and the other regions and how an efficient treatment of problem a-g is distributed between the different regions. With a transmission capability of P MW between region X and other regions, the challenges are now modified to:

- a. There must be enough power plants at low wind. This is valid for region X and could include maximum P MW of imported power, if this is available in neighboring regions.
- b. There must be enough power plants with fast control at high wind situations. At high wind situations, there could be export from region X. This then means that the needed fast controllable sources could be outside region X. Sometimes even more than P MW (but < 2P MW) could be used from other regions since export could change to import during fast changes.
- c. The system must be robust enough to survive a dimensioning fault. Even internal faults in X should not cause severe problems outside X and vice versa.
- d. There must be enough reserves covering all possible uncertainties of supply and demand (system net imbalances), for example situations with large decrease of total wind power production. Like in the previous section, this can be a dimensioning criterion for slower reserves. This type of reserve could be available within the X region or in neighboring regions considering the trading capacities between the regions.
- e. Handling of possible problems in the internal grid. Here the interconnections must be considered, since all imbalances in one part of region X can be balanced in another region, which is electrically closer than the other part of region X.

f. Possibility to regulate down available wind power during low power consumption. Here down regulation is only needed if wind power in X is larger than local load plus possible export.

g. Possibility of continuous control of wind power. Continuous control of wind power in X is only needed when required balancing is not available in other power sources within or outside X considering the limited trading capacity.

IV. EXAMPLES OF WIND POWER IN DIFFERENT REGIONS

As shown above, there are several aspects that have to be considered in order to find out the consequences of having a certain amount of wind power in a region. Below some examples concerning experiences of considerable wind power production in a region are shown and commented. These are actual examples, from real power systems.

A. Example Wind power on Gotland

Table I shows the situation in the year 2005 for the Swedish island Gotland, which is connected to mainland Sweden with a HVDC line. Wind power on Gotland covers 19% of the energy consumption on the island. All balancing of net load changes is performed on the mainland. The capacity of the connection to the mainland is 180 MW, i.e., the *maximal share of wind power* is 40% (see definition in eq. 1), i.e., the installed wind power covers at most 40% of possible lowest net consumption, which is lowest local consumption + possible export:

$$\text{Maximal share of wind power} = \frac{\text{Maximal wind power}}{\text{Lowest consumption} + \text{possible exchange}} = \frac{90}{45 + 180} = 40\% \quad (1)$$

This is conservative, as the probability of maximum wind power at the same time as lowest load is very small. This implies that there is a rather large margin up to situations corresponding to problem b in section 3.

TABLE I. DATA FOR GOTLAND

	Min MW	Max MW	GWh/year
Power consumption	45	160	930
Wind power	0	90	180 (19%)
Export capacity	0	180	

It must be noted that sometimes the produced wind power on Gotland exceeds the local load. This implies that in these situations the current in the HVDC line has to go in reverse direction compared to the normal feeding of the island. This made it necessary to introduce some control equipment in order to be able to handle situations when wind power on Gotland is about the same as the load on Gotland. When this happens, the power on the HVDC line is almost zero, which requires special

arrangement to be able to change the power flow direction often.

The experience reported for the issues a)...g) are collected in Table IV.

B. Example: Wind power in Denmark

TABLE II shows the situation in the year 2005 for West Denmark. The two parts of Denmark are not connected. Denmark West is synchronously connected to the European continent, the UCTE system, while Denmark East is synchronously connected to the North European system, the Nordel system. Denmark West has several connections with neighboring countries with a total capacity of about 2830 MW (Norway 1000 MW, Sweden 630 MW, Germany 1200 MW), Denmark East has connections with a total capacity of about 2300 MW (Sweden 1700 MW, Germany 600 MW).

Wind power in East Denmark covers 12% of the energy consumption and in West Denmark 24% of the energy consumption.

In West Denmark the installed wind power covers at most 58% of possible lowest net consumption, which is lowest local consumption + possible export:

$$\text{Maximal share of wind power} = \frac{\text{Maximal wind power}}{\text{Lowest consumption} + \text{possible exchange}} = \frac{2380}{1266 + 2830} = 58\%$$

(2)

Since Denmark East and West are not connected wind power has to be balanced separately in both areas. The maximal share of wind power is 58% in Denmark West and 23% in East.

TABLE II. DATA FOR WEST DENMARK.

	Min MW	Max MW	TWh/year
Power consumption	1266	3697	21.1
Wind power	0	2380	5.0 (24%)
Export capacity	0	2830	

This implies that theoretically there is room for more wind power in Denmark West, but here also the significant heat bound power production has to be taken into account, although this production is low in summer, where the lowest power consumption is. The lowest production left for wind, might be in a winter hour with large heat bound power production. The lowest consumption after removing of decentralized production was 764 MW in 2005; this gives 66% as maximal share of wind power. If the heat bound power production from centralized production is also taken into account the share is even larger, sometimes above 100%. Before the decentralized production came to working according to market signals 1st of January 2005, it was more necessary to cut down the wind production than after that date, because the production was bigger than consumption and export possibility on occasions when German export was limited due to large wind power production in the North of Germany. Curtailing wind power has not happened so

often since then.

The experience reported for the issues a)...g) are collected in Table V.

C. Example Wind power in Schleswig-Holstein

At the end of 2005, wind farms with a total installed capacity of around 7,564 MW were connected in the E.ON Netz control area, accounting for 41% of total installed wind power capacity in Germany. More than one fourth of installed capacity is located in the northern part of the control zone of E.ON Netz in Schleswig-Holstein.

E.ON Netz is responsible for a secure and reliable operation of the transmission system. To guarantee the security of supply and therefore a balance between generation and consumption of electrical energy control power is required by the transmission operator at all times. A certain amount of this control power is dedicated to balance deviations of the actual wind power in-feed from its day-ahead prognosis. Therefore E.ON Netz has to tender and purchase adequate control power both for in-hour variations and on basis of the day-ahead wind power prognosis.

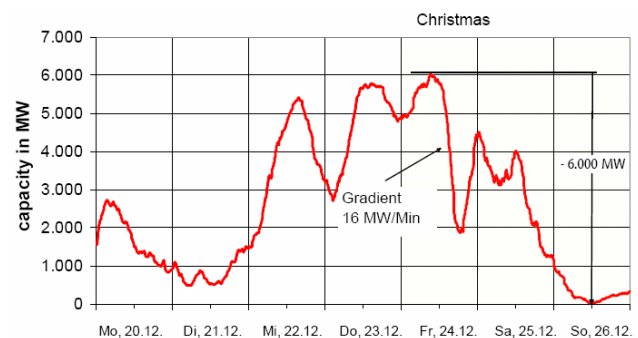


Fig 3. Wind power production in E.ON Netz area over one week December, 2004 [9].

In the E.ON Netz grid wind power in-feed decreases of 16 MW/minute have happened. Within a few hours the feed-in capacity can experience large changes frequently. Fig 3. reproduces the course of wind power feed-in during the Christmas week from 20 to 26 December 2004. Whilst wind power feed-in at 9.15am on Christmas Eve reached its maximum for the year at 6,024MW, it fell to below 2,000MW within only 10 hours, a difference of over 4,000MW. This corresponds to the capacity of 8 x 500MW coal fired power plant blocks. On Boxing Day, wind power feed-in in the E.ON grid fell to below 40MW. Handling such significant differences in feed-in levels poses a major challenge to grid operators, especially as the forecasting of these changes is not always correct.

The example of Schleswig-Holstein shows surplus wind power on windy days. Whereas total electricity consumption (grid load) is between ca. 750 MW (low load) and ca. 2000 MW (high load), wind farms with a total production capacity of over 2200 MW are installed in the area (TABLE III).

Consequently, even at periods of high consumption,

around four times as much electricity is generated by wind power on windy days than is used by customers. This surplus wind power has to be transported to consumers over long distances. The size and operation of the grids must be altered to cope with this requirement, with the primary objective of avoiding overloading lines and the resulting losses of supply.

TABLE III. DATA FOR SCHLESWIG-HOLSTEIN.

	Min MW	Max MW	TWh/year
Power consumption	750	2000	12.6
Wind power	0	2275	4.2 (33%)
Export capacity	0	4400	

In Germany the Renewable Energy Sources Act of 21 July 2004 stipulates among others the priority connection of installations for the generation of electricity from renewable energies to the general electricity supply grids and the priority purchase and transmission of this electricity. Therefore a continuous control of wind power is not possible. However, the large rapid expansion of the installation of wind farms in Schleswig-Holstein means that on windy days, the grid capacities are entirely exhausted. Although E.ON Netz instituted grid expansion measures at an early stage, it must be assumed that it will take several years before the planned power lines are built. In order to be in a position to connect further renewable energy generators before the grid expansion is completed, E.ON Netz has developed the so-called generation management as a transitional solution. Generation management involves the intermittent reduction of the power fed in by the renewable energy generators, in order to protect grid equipment such as overhead lines or transformers from feed-in-related overloads, thereby avoiding supply failures. In mid 2003, E.ON Netz implemented generation management in all ten regions in Schleswig-Holstein and in the first half of 2005 in the first regions within Lower Saxony.

The experience reported for the issues a)...g) are collected in Table VI.

V. CONCLUSION

This paper reports on the experience of regions where wind power produces 20-35 % of yearly gross demand.

The regions are part of larger power systems, however, some impacts due to large wind power production can be seen.

In all the regions, the “maximal wind power” is considerably less than minimum load plus export possibility. In Gotland island all issues of reliability are solved outside the region with the flexible HVDC connection to mainland. In Denmark and Germany, most issues due to variability of wind are solved outside region.

From the experience reported, it seems that when making sure that the following aspects are covered, the wind power can be managed as a combined inside/outside region solution:

- the interconnectors can react fast enough
- most of the wind farms do not trip off due to grid faults and thus cause a dimensioning fault
- it is possible to curtail the wind power production in critical (rare) occasions

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TABLE IV EXPERIENCE FROM GOTLAND. WIND ENERGY COVERS 19 % OF GROSS DEMAND AND THE MAXIMAL SHARE OF WIND POWER IS 40 %.

Problem		Gotland	Solution region?
a	Enough power plants at low wind	Import capacity from mainland enough. Local gas turbines for emergency situations.	Solved mainly outside region.
b	Enough power plants with fast control during high wind	The HVDC to mainland is easy to control, also around 0 MW (control enhanced to enable this), and from mainland side point of view wind power on Gotland is comparatively small	Solved outside region.
c	The system must survive a dimensioning fault.	Wind power would be part of dimensioning problem in cases of transmission faults. The HVDC link and mainland production can act as reserve.	Solved outside region.
d	Enough reserves at large decrease of total wind power	The HVDC to mainland is easy to control, and all balancing is therefore performed on the mainland. From mainland point of view, wind power production on Gotland is comparatively small.	Solved outside region
e	Handling of problem in internal grid	Reactive power support from synchronous compensator and a local HVDC-VSC (Voltage Source Converter). Not a limiting factor, except for c.	Voltage problem only within each region because of HVDC.
f	Possibility to down regulate wind power	Used frequently up to 2003 when the possibility to controllability around 0 MW on the HVDC was installed.	Currently only at rare grid problems.
g	Possibility of continuous control of wind power	Not implemented, since there are local gas turbines and a 35 MW diesel plant that are started at an outage of the HVDC link	Only of interest at isolated operation (very rare).

TABLE V EXPERIENCE FOR WEST DENMARK. WIND ENERGY COVERS 24 % OF THE YEARLY ELECTRICITY CONSUMPTION AND THE MAXIMAL SHARE OF WIND POWER IS 58 %.

Problem		Denmark West	Solution region?
a	Enough power plants at low wind	Power production capacity enough	Solved inside region
b	Enough power plants with fast control during high wind	Regulating power (10 minutes) is traded at the Nordic TSO's regulating power market (NOIS) and can be supplied from all Nordpool members, within the limit of the DC connections to Sweden and Norway. From the importer's point of view wind power in West Denmark is comparatively small	Solved in the Nordpool region (inside and outside region)
c	The system must survive a dimensioning fault.	Dimensioning fault is large conventional power plant or transmission line.	Solved inside and outside region
d	Enough reserves at large decrease of total wind power	Regulating power (10 minutes) is traded at the Nordic TSO's regulation power market (NOIS) and can be supplied from all Nordpool members. The HVDC to Sweden and Norway is easy to control, and from the Nordic Power System's point of view the necessary positive regulation power for West Danish wind power is comparatively small, but its availability is varying.	Solved inside and outside region
e	Handling of problem in internal grid	Reactive power support from synchronous compensator. Not a limiting factor, except for c.	Voltage problem is solved locally.
f	Possibility to down regulate wind power	Has been used, but very seldom	Currently only at rare grid problems.
g	Possibility of continuous control of wind power	Regulation capacities used as needed for one large wind farm. It's also possible to cut off wind farms. Of interest only at isolated operation	Only at large offshore wind farm.

TABLE VI EXPERIENCE FROM SCHLESWIG-HOLSTEIN. WIND ENERGY COVERS 33 % OF THE YEARLY ELECTRICITY CONSUMPTION AND THE MAXIMAL SHARE OF WIND POWER IS 18 %.

Problem		Schleswig-Holstein	Solution region?
a	Enough power plants at low wind	In principle enough power plants are available in that region.	Solved inside region
b	Enough power plants with fast control during high wind	In principle enough power plants are available in that region (Since TSOs are not dealing with unit commitment as far as no congestion limits are exceeded and since the region is part of the interconnected power system of the UCTE power plants will be operated according to availability and costs.).	Solved inside and outside region
c	The system must survive a dimensioning fault.	Faults in the extra-high voltage grid can result in a sudden failing of a huge number of wind power plants in the affected region: up to 3,000 MW can fail, thereby putting the grid stability at risk [10]. In general outages of more than 3,000 MW are defined as endangered in the UCTE synchronously interconnected system. For further expansion of wind power, grid connection regulations are continuously improved by E.ON Netz to take care of grid stability and supply reliability.	Has to be solved inside region in future (grid codes with Fault-Ride-Through to avoid wind power becoming dimensioning fault)
d	Enough reserves at large decrease of total wind power	E.ON Netz has to tender and purchase adequate control power as well on basis of the day-ahead wind power prognosis.	Solved inside and outside region
e	Handling of problem in internal grid	Voltage regulation has to be solved locally, as long as there are enough power plants online this is not a limiting factor (see answer to problem b). New wind farms have to contribute to the reactive power supply and voltage regulation. Depending on their size new wind farms have to keep either a certain power factor or have to feed in a certain amount of reactive power, which is given by the control centre, or have to participate in voltage regulation.	Voltage problem is solved locally. New wind farms are contributing.
f	Possibility to down regulate wind power	In mid 2003, E.ON Netz implemented generation management in ten regions of Schleswig-Holstein	Has been used since 2003
g	Possibility of continuous control of wind power	A continuous control of wind power is not possible due to the feed-in law (Renewable Energy Sources Act, 21.7.2004)	