Improving wind power quality with energy storage

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Improving wind power quality with energy storage

C.N. Rasmussen

Abstract-- **The results of simulation of the influence of energy storage on wind power quality are presented. Simulations are done using a mathematical model of energy storage. Results show the relation between storage power and energy, and the obtained increase in minimum available power from the combination of wind and storage. The introduction of storage enables smoothening of wind power on a timescale proportional to the storage energy. Storage does not provide availability of wind power at all times, but allows for a certain fraction of average power in a given timeframe to be available with high probability.**

The amount of storage capacity necessary for significant wind power quality improvement in a given period is found to be 20 to 40% of the energy produced in that period. The necessary power is found to be 80 to 100% of the average power of the period.

Index terms-- **Energy storage, Wind energy, Simulation, Power quality, Power generation availability.**

I. INTRODUCTION

Wind power is a rapidly growing and very promising renewable source of electric energy. But with a large fraction of wind power in the electricity supply network, the stochastic nature of wind power will start to play a significant role. A controllable and non-fluctuating supply is needed to fully secure availability, but this cannot be achieved with wind power alone.

Introducing an energy storage element in connection to a wind power plant changes the spectrum and statistical distribution of the output power. Increasing the amount of storage (power and energy), associated with a wind power plant, will gradually make the output more controllable and predictable.

A variety of energy storage technologies with diverse properties and attributes are available. In order to determine, which storage technologies that are most relevant in connection to wind power the necessary power- and energy level of energy storage must be determined. The aim of using energy storage is to improve wind power quality, but the actual improvement is subject to an objective judgment. What is presented here is the result of an effort to determine the power quality improving effect of energy storage on medium timescales, from minutes to days. Power quality improvement will be viewed in three different ways:

- Availability improvement; increasing the likelihood of a certain amount of power being present in a given timeframe.

- Variability reduction; reducing the size of power fluctuations from average, or from an initial power level.

- Predictability improvement; reducing the difference between forecast and actual power.

When viewing power quality from this perspective it is possible to quantify the term wind power quality and establish a connection between the amount of energy storage (power and energy) and the obtained quality improvement.

In order to evaluate the whole concept of energy storage in relation to wind energy it is important to know how much storage that is needed to obtain the desired effect. Such information can be used to help choose the most optimal storage technology.

II. ENERGY STORAGE TECHNOLOGIES

A variety of technologies are available for storage of energy in the power system. When identifying the most relevant storage solutions it is necessary to include considerations on many relevant parameters, such as: cost, lifetime, reliability, size, storage capacity and environmental impact. All these parameters should be evaluated against the potential benefit of adding storage to reach a decision on which type of storage should be added. There may also be cases where the value of adding storage is not large enough to justify such an investment.

Energy storage technologies for power applications can be divided into three groups: Mechanical, electro-chemical and electromagnetic storage. Mechanical storage includes pumped hydro storage, compressed air energy storage and flywheels. Electro-chemical storage includes all types of batteries and fuel cells, and electromagnetic storage includes super capacitors and superconducting magnetic energy storage.

Each technology has certain attributes with regard to storage capacity, power, reaction time and cost. Grouping storage technologies with regard to storage capacity is relevant because it can be used to exclude those sizes not relevant in relation to wind power.

Figure 1 shows the most relevant storage technologies grouped according to energy storage capacity. The medium capacity storage technologies, with realistic storage sizes in the range of 10 MWh, seem most relevant for storage in relation to wind power. The medium capacity storage technologies are batteries, flow batteries and fuel cells, which all have the advantage in relation to wind power plants that they are modular and scalable.

In the low capacity end, ultra capacitors may also be of relevance in relation to wind power. Hydrogen fuel cells may be relevant, both as medium- and high capacity storage.

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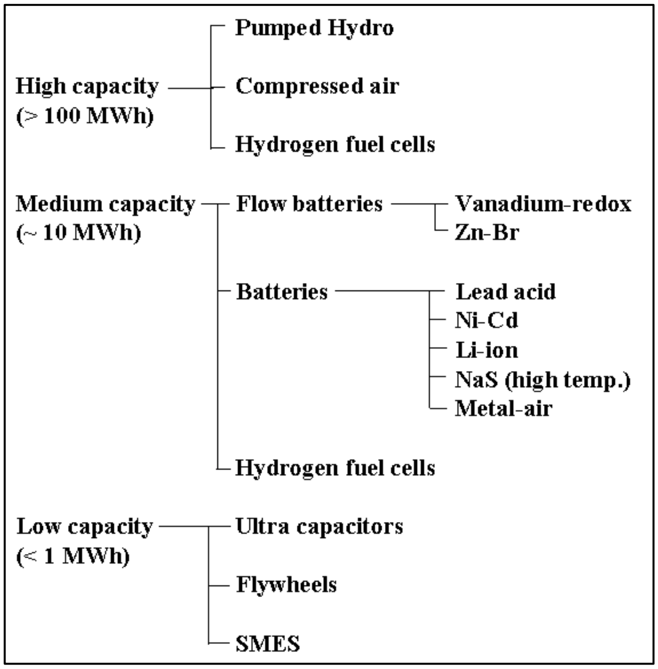

Figure 1. Energy storage technologies grouped according to storage capacity.

The low capacity storage technologies seem less relevant in relation to wind power because of high cost pr. unit stored energy and relatively short storage time scale. The very high capacity technologies, pumped hydro storage and compressed air storage (CASE), also seem less relevant because of the large investments and civil engineering efforts required, as well as special requirements with regard to placement.

III. WIND POWER QUALITY IMPROVEMENT

In order to obtain a clearer view of which kinds of improvements to power quality that an energy storage device can contribute with, some possible applications are listed below.

A. Spinning reserve and stand-by reserve

Short term storage of up to perhaps 1 min of supply could enhance the apparent inertial constant of the wind park, reduce short-term variations and provide enhanced “spinning reserve” to a windmill or wind farm.

Energy reserves of up to 15 min of supply would allow shutdown of smaller stand-by units such as local combined heat-and-power units. During periods of low load the storage would charge up to its maximum state of charge and stay in this state until a sudden reduction in available power occurred.

B. Peak shaving

Peak shaving is removal or reduction of large deviations from average, on time scales, which depends on storage capacity, from seconds to several minutes.

C. Wind power filtering

A general reduction of wind power fluctuations can be obtained by running the energy storage as a kind of low-pass filter. The smoothening effect will depend on the power and storage capacity of the storage, as well as the variability of the wind. The time horizon of such a usage would stretch from seconds up to hours or days, depending on storage size. In the simulations presented here, the availability increases and variability reductions are obtained by running the storage as a filter.

D. Improving predictability

Being able to meet a production forecast is of large value. This would typically be a forecast of 12 to 48 hours ahead and the ability to follow the predicted production of such a forecast could be improved by the use of energy storage.

E. Long-term load leveling

In case of large amounts of energy storage, long-term load leveling could be obtained. This would for example allow the use of wind farms as base load or enable an increase of predictability to nearly 100% for a certain period of time. The time horizon could be days or weeks, depending on storage size and the allowed variations. Such storage levels could for example allow for shutdown of larger stand-by reserves.

In case of the electric energy production being based primarily on renewable energy sources, a very large amount of energy storage would have to be combined with a significant overcapacity in generation.

IV. THE NATURE OF WIND POWER VARIATIONS

Wind power production (P_w) varies with wind speed (v) approximately as [3]:

$$P_W(v) = \begin{cases} 0 \text{ for } v < v_{min} \\ P_n \cdot \left(\frac{v}{v_n}\right)^3 \text{ for } v \in \left[v_{min}; v_n\right] \\ P_n \text{ for } v \in \left[v_n; v_{max}\right] \\ 0 \text{ for } v > v_{max} \end{cases} \qquad (1)$$

With v_{min}, v_n and v_{max} being the minimum, nominal and maximum wind speeds of the wind generator. P_n is the nominal wind power. Typical parameter values could be v_{min}= 4 m/s, v_n= 13 m/s and v_{max}= 25 m/s.

The wind varies in a stochastic way with statistical distribution of wind speeds close to that of a Weibull distribution [1], [2], [5]. The transformation of wind speed into wind power using (1) causes the statistical distribution to change but it still follows a Weibull distribution fairly accurately.

Different wind sites experience different statistical distributions of wind speed. The wind sites can be divided into classes according to average and standard deviation of the wind speed [5]. Table 1 shows the average wind speed (μ), standard deviation (σ) and turbulence intensity factor $I_\mu=(\sigma/\mu)$ for 4 wind classes, calculated with characteristic turbulence intensity factor I_{15} = 0.14.

TABLE 1
Statistical parameters for 4 IEC wind classes used for the model results presented here [5].

Class #	1	2	3	4
μ [m/s]	10	8.5	7.5	6
σ [m/s]	1.63	1.49	1.4	1.26
I_μ	0.163	0.175	0.187	0.21

The statistical parameters do not define the variation spectrum. The performance and required power and storage capacity of an energy storage is strongly influenced by the variation spectrum which means that knowledge of this is essential.

Wind variations are generated by atmospheric phenomena which take place on many orders of magnitude, with regard to both space and time [3]. The scales of these variations range from local turbulence on length scales of meters and timescales of seconds to seasonal variations on global scales. It therefore seems reasonable to assume that wind variations should range on timescales from approximately $(d/\mu) \sim 10$s up to perhaps 1 year. With $d \sim 100$m being a characteristic dimension of the wind generator and $\mu \sim 10$ m/s being the average wind speed. An analysis of various sets of wind data shows that the wind spectrum has a strong degree of self-similarity, which is characteristic for fractals. Figure 2 shows the power spectrum of a 2MW generator, on a time scale from 1 hour up to 2000 hours (~2½ months). There is a linear relationship between log(t) and log(P) which corresponds to a power-law relation:

$$P(t) = t^n \tag{2}$$

With $t=f^{-1}$ being the time scale. The slope (n) of the line turns out to be ~1. According to [4], the case of n=1 corresponds to self-similarity with a fractal dimension of D=1.5. An analysis of other data sets shows that this relation continues at least down to t ~ 6 minutes, but the slope tends to decrease on timescales above ~½ year. A decreasing slope corresponds to larger fractal dimension (D>1.5) and thereby a rougher appearance on larger scales.

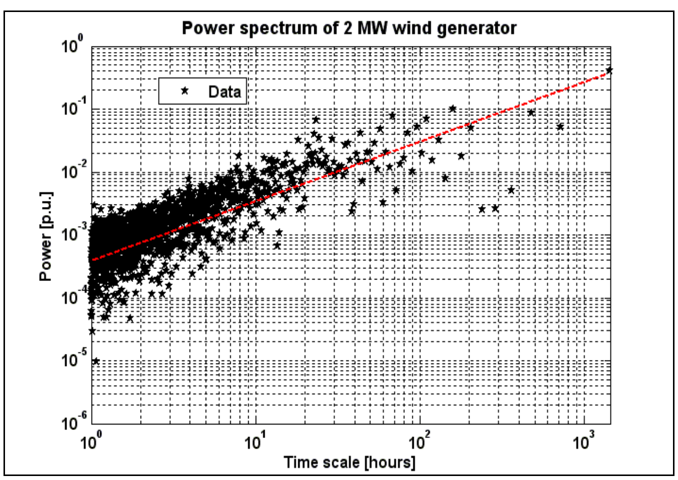

Figure 2. Frequency spectrum of wind power from 1h to 2000h. The line has a slope of 1 in the double-logarithmic plot.

A self-similar wind pattern means that a plot of wind power versus time appears similar on any time scale.

This behavior of the wind points to a linear relation between required energy storage capacity and the time scale on which wind power is to be guaranteed or smoothened.

V. ENERGY STORAGE MODELING

When modeling the effect of energy storage on power quality, a set of storage properties and a control scheme of the storage must be chosen. In these simulations the amount of parameters has been kept as low as possible. The parameters include maximum storage power, energy capacity, charge and discharge efficiencies and preferred state of charge.

The basic equations describe the relation between storage energy (E_s) and power (P_s):

$$\frac{dE_s}{dt} = \frac{-P_s}{\varepsilon(P_s)} \tag{3}$$

$$P_s = (P_{req} - P_w) + \frac{(E_s - E_{max} \cdot psoc)}{\tau} \tag{4}$$

With $\varepsilon = \varepsilon_c = \varepsilon_d$ being the charge or discharge efficiency, P_w is the available wind power, E_{max} is the maximum energy storage capacity, psoc is the preferred state of charge and τ is a time constant with which the storage tries to reach the preferred state of charge. P_{req} is the required power of wind and storage combined. The power requirement can be manually controlled or it can be found using an algorithm. For these simulations the power requirement P_{req} at a given time is found as the average wind power over a past period of length Δt:

$$P_{req} = \frac{1}{\Delta t} \int_{t-\Delta t}^{t} P_w \, dt \tag{5}$$

In this way the energy storage acts as a filter that tries to eliminate fluctuations on timescales below Δt. The ability to do this depends on power and storage capacity.

The purpose of this simulation model, which has been implemented in MATLAB, has been to introduce different wind distributions and simulate the resulting power output from wind and storage combined. By looking at the resulting statistical distribution of the combined output it is possible to determine the obtained improvement in power quality, as function of storage energy and power.

Wind distributions can be found from actual sets of wind-data or they can be generated artificially using an algorithm [2], [6], which generates a temporal wind pattern with a specified average and standard deviation. This algorithm does in fact produce a Weibull distributed wind pattern and the parameters can be set to imitate any wind class. The self-similar pattern with power spectrum according to (2) also appears. This seems to justify the use of a wind generation algorithm for making data sets to be used in the energy storage simulation model.

VI. SIMULATION RESULTS

For these simulations, three ways of viewing power quality improvement has been treated. The influence of maximum storage power and energy capacity, on availability, variability and predictability has been investigated. These properties of wind power are defined in the following and the results are presented.

Looking at a wind power profile and the corresponding response of the energy storage shown in figure 3 gives an idea of how a storage facility with control scheme governed by equations 4 and 5 will influence the total power output. In this case the storage efficiency is set to E_{ff} = 100%. The storage capacity is equal to 1h of nominal power, or ~8% of the energy E_{tot} produced in the given time period, and the storage power equals nominal power P_n. The effect of storage is to remove large power fluctuations and provide a response-delay.

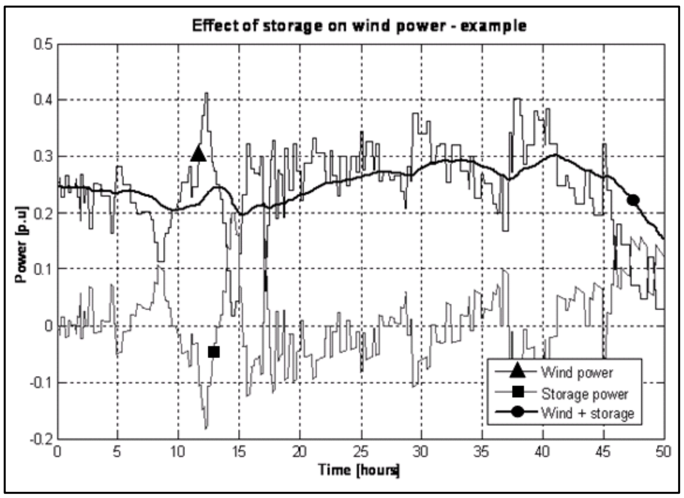

Figure 3. The effect of introducing energy storage on total power output.

The statistical distribution of the total power from wind plus storage is more uniform than that of wind power alone. Figure 4 shows the change in cumulative distribution function of the power profile shown in figure 3, from wind alone to wind and storage combined. Since E_{ff} = 100% the average power does not change but the fraction of times with very high or very low power becomes smaller. Figure 4 shows that with a storage capacity which is 8% of the energy produced during the 50h timeframe, a significant fraction of average power will be available with high probability. As an example; ~75% of average power will be available with 95% confidence during the period. Without storage only ~30% of average power will be available with 95% confidence.

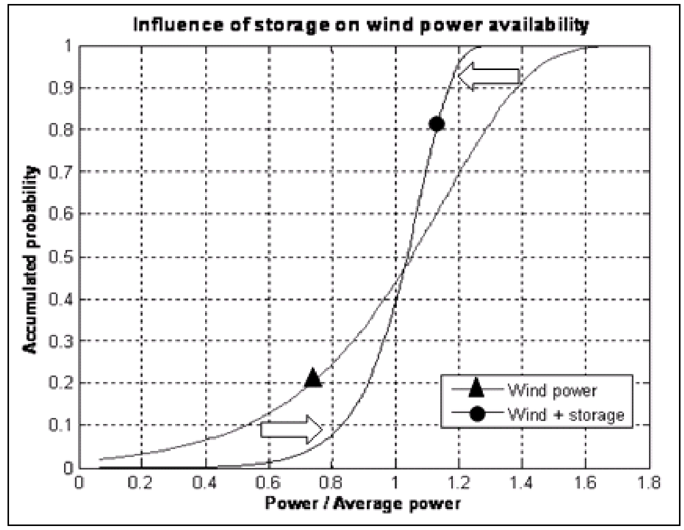

Figure 4. Change in cumulative distribution function of power output as a result of the introduction of energy storage with storage power P_n and storage energy capacity equal to 8% of E_{tot}.

A. Availability increase

A relatively larger fraction of average power in a given time frame can be made available with a certain probability if storage is introduced. Power, energy capacity and efficiency of the storage will determine how large a fraction of average power that will be available. It is important to acknowledge that no amount of power will be available at all times. The level of availability refers to any specific period Δt in which the average power is P_{avg} and the produced energy is $E_{tot}=P_{avg}\cdot\Delta t$. Because of the self-similar behavior of the wind pattern, the length of the time interval Δt does not influence the levels of availability when plotted as function energy in units of total energy produced and with power in units of average power of the period.

The wind patterns used for availability calculations have been made using the previously described algorithm, thus allowing for creation of wind profiles with a variety of statistical power distributions. The charge efficiency ε_c and discharge efficiency ε_d was set to 85%. The total efficiency of wind and storage combined may be calculated as:

$$E_{ff} = (1 - f_s) + f_s \cdot \varepsilon_c \cdot \varepsilon_d \qquad (6)$$

In (6), f_s~0.5 is the fraction of generated power that passes through the storage. This results in $E_{ff} \approx 86\%$ and $P_{max}=E_{ff}\cdot P_{avg}$ is the maximum available power that can be guaranteed in a period, regardless of how large the storage power and energy is made.

Availability is here defined as the fraction of maximum available power P_{max} that is available with a certain probability in a given period Δt.

The results show that in order to be able to obtain a situation where a fraction of average power P_{avg} is available during the period Δt, with a certain probability (x%), the storage energy capacity must be a certain fraction of the energy produced in that period $E_{tot}=P_{avg}\cdot\Delta t$ and storage power must be a certain fraction of average power. Figure 5 shows a contour plot of power availability (95% confidence) for a class 1 wind distribution (strong average wind).

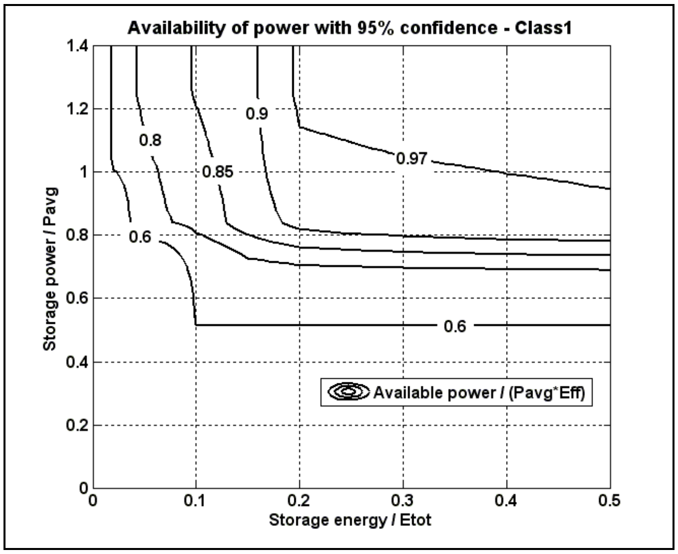

Figure 5. Power available with 95% confidence, as function of storage power and storage energy, in any time period Δt with average wind power P_{avg} and total wind energy of $E_{tot}=P_{avg}\cdot\Delta t$. The available power is in units of maximum available power P_{max}. Wind class 1 distribution.

From figure 5 it can be deducted that with an energy capacity of $\sim0.2\cdot E_{tot}$ it is possible to provide >90% of maximum available power $P_{max}=E_{ff}\cdot P_{avg}$ with 95% confidence, if the storage power is $>0.8\cdot P_{avg}$.

The average wind speed does not influence availability because of the dimensionless definition. But increasing the turbulence intensity factor (making the wind fluctuate more) has the effect of increasing the storage energy capacity required to obtain the same level of availability, as it is seen when comparing figures 5 and 6.

The actual amount of energy produced is much smaller for a class 4 site, but the required amount of energy storage capacity is equal to, or larger, than that of a class 1 site. In order to guarantee >90% of P_{max} with 95% confidence for a class 4 site, the required energy capacity is $\sim0.4\cdot E_{tot}$ with a storage power of $\sim0.9\cdot P_{avg}$.

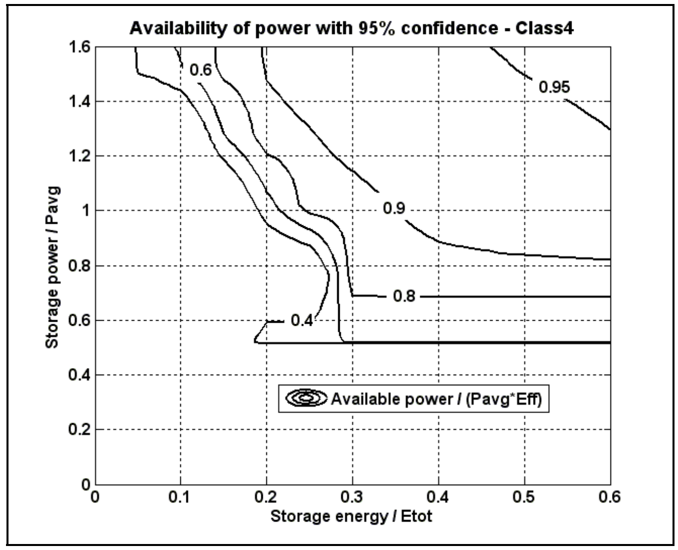

Figure 6. Power available with 95% confidence as function of storage power and storage energy, in any time period Δt with average wind power of P_{avg} and total wind energy of $E_{tot}=P_{avg}\cdot\Delta t$. Wind class 4 distribution.

A storage device can therefore not be made to guarantee anything at all times but within a given timeframe the storage can guarantee a fraction of the power average for that timeframe. This fraction depends on energy capacity, power and efficiency of the storage. This could be used for example to reduce the changes in output of additional power generation equipment such as CHP-plants, or to provide a running-delay that can ensure a certain amount of power for a specified time into the future.

If for example the requirement is 90% of average power, with 95% confidence, 30 minutes ahead, for a 1 MW wind turbine at a class 1 site, then the required energy and power of the storage can be found from figure 5. The required energy is $\sim0.2\cdot0.5h\cdot1MW \approx 100kWh$ and the required power is $\sim0.8\cdot1MW \approx 800kW$. If the requirement level is only such, that 90% of long-term average power for the site P_{avg}(site) should be available, then a smaller fraction $C_f=P_{avg}(site)/P_n$ of nominal power and energy is required. Table 2 shows the required energy and power for a 1MW generator at two different sites, and with 90% of nominal power or 90% of average long-term power as availability requirements.

TABLE 2
Required storage energy and power, for a 1MW wind generator at two different sites and with two different requirement levels.

Timeframe (Δt)	30 min	30 min	30 min	30 min
Confidence	95%	95%	95%	95%
Availability	90%	90%	90%	90%
Wind class #	1	1	4	4
P_{avg}/P_n	1	0.47	1	0.24
E_{tot} [kWh]	500	235	500	120
$E_{s\text{-}req}$ [kWh]	100	47	200	47
$P_{s\text{-}req}$ [kW]	800	376	900	216

The required storage energy and power, for smoothening with a 30-min timeframe, are shown in the two bottom rows. Ensuring a fraction of P_n obviously demands more storage energy and power than just ensuring a fraction of the long-term average wind power of that site. The simulations show that ensuring availability of wind power on a time scale of Δt, requires storage energy capacity of approximately 0.2 to 0.4 times the energy produced in Δt and power of 0.8 to 1 times the power average of Δt. For smoothening to be effective the storage energy E_s and power P_s must therefore be:

$$E_s(\Delta t) = \alpha \cdot C_f \cdot P_n \cdot \Delta t \quad ; \quad \alpha \in [0.2;0.4]$$
$$P_s = \beta \cdot C_f \cdot P_n \quad ; \quad \beta \in [0.8;1] \qquad (7)$$

A study of energy storage in relation to a wind power plant in Taiwan [7] indicated storage requirements of $E_s \approx 0.17$ - $0.27 \cdot E_{tot}$ and $P_s \approx 0.46$ – $1.1 \cdot P_{avg}$ to obtain complete power leveling in a given period Δt. This is in good agreement with the results obtained here.

B. Variability reduction

Variability can for example be defined as the maximum deviation from average power in a given period Δt. Or it can be defined as the maximum deviation from the power available at the beginning of the period. In many cases it may only be necessary to look at the negative power deviations, which are the reductions in available power relative to the average. When applying this viewpoint there is not much difference between availability and negative variability. Variability is given as the standard deviation of the statistical power distribution. As figure 4 shows, the effect of adding storage is to reduce the standard deviation and thereby also making a larger fraction of average power available. In figure 7, simulated levels of variability within one hour, at class 4 sites, are shown.

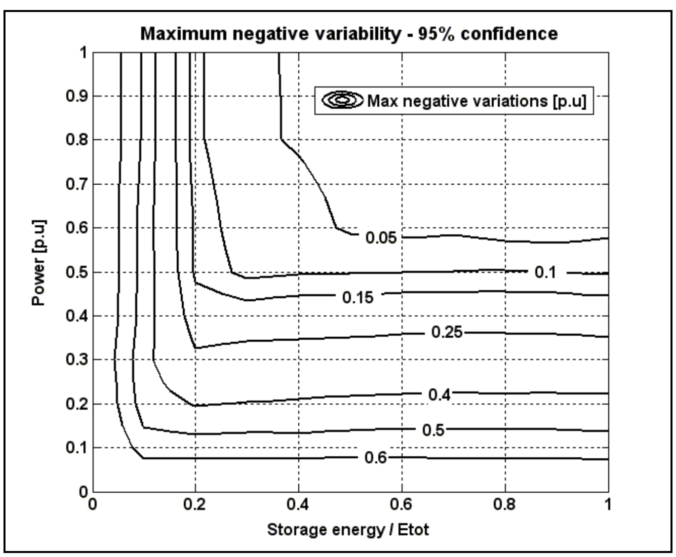

Figure 7. Reduction in wind power variability with energy storage. Maximum power reduction at a class 4 wind site.

With storage power of $>0.5 \cdot P_n$ and storage energy of $>0.3 \cdot E_{tot}$ the maximum variations in negative direction can be kept below $0.1 \cdot P_n$. Not surprisingly, the storage requirement for significant reduction in negative variations is the same as the requirement for a large increase in availability.

C. Predictability improvement

It may be required by owners of wind power plants that they provide a power generation forecast of for example 12 to 48 hours ahead. The accuracy of such a forecast could be improved with energy storage by absorbing a fraction of the deviations from the forecast. The storage energy needed for this purpose depends on the length of the timeframe for which wind power should be predicted as well as the size and variation pattern of the error.

The forecast power error, which is the difference between forecast and actual wind power, may be divided into a systematic and a random component [3]. The power required by a storage device in order for it to effectively reduce forecast errors will be approximately equal to the rms-value of the forecast error e_{rms}.

The required storage energy will largely depend on the systematic error (μ_e) since the random error will fluctuate around the systematic error on a much shorter timescale and only add a small contribution to the storage requirement. Using data from [8], the rms-value of the forecast wind power error for the North Sea area is calculated to ~0.2 p.u., whereas the systematic error is found to be ~0.1 p.u. for the same area. This means that the required energy capacity for energy storage used for forecast improvement is on the order of $\sim 0.1 \cdot P_n \cdot \Delta t$, with Δt being the length of the forecast timeframe. With a 36-hour timeframe the energy requirement thus becomes very large.

VII. CONCLUSIONS

The quality of wind power, defined here as availability, reliability or predictability, may be improved by introducing energy storage. The results obtained can be used to determine the relevant level of storage for a given timescale and nominal power. Ensuring a reasonable fraction of average power, on timescales from minutes up to hours, seems obtainable with the use of battery storage.

The storage energy and power requirement, for significant availability improvement in a given period, is found to be 20 to 40% of the energy produced in the period and 80 to 100% of average power for the period. The storage requirements for significant power quality improvement for e.g. a 1MW wind generator, on a 30 minute timescale, are approximately 380kW of power and 50kWh of energy.

Ensuring availability and reducing variability are two strongly coupled ways of looking at improvement. Making power more available means making it more predictable, reliable and controllable. Because of the stochastic and self-similar nature of wind power, ensuring any significant level of wind power at all times, would demand an energy storage capacity of up to 40% of the yearly energy production, this seems unrealistic. The prospect of energy storage is rather to remove fluctuations on shorter timescales (seconds to hours) in order to improve power quality.

Predictability can be improved with storage and the required power is limited. But timescales of ~36 hours result in a large energy requirement unless the systematic prediction error is very small.

VIII. ACKNOWLEDGEMENTS

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X. BIOGRAPHY

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