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Energy storage options for improving wind power quality

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***Abstract*— The intermittency of wind may in some cases limit the applicability of wind power when integrated directly into the distribution network. Energy storage technologies can provide a local solution either through peak shaving or increasing temporal stability of the power generation. In this work the needs and options for peak shaving storage are investigated with practical implementations through case studies. It is demonstrated, that roughly 1 MWh storage per MW of wind power is enough to reduce at least 10% of the local voltage rice in weak networks. The weaker the network is, the more the storage influences the local network voltages.**

***Index Terms*—energy storage. power quality**

I. INTRODUCTION

The wind speed fluctuates on several time scales due to movement of air masses and numerous meteorological phenomena. These variations influence wind power both in terms of consistency of generated power which causes power quality concerns when wind power is integrated into the energy systems. The consequent intermittency of wind power may cause imbalance between local power demand and power generation which in turn may lead to adverse voltage variations and other effects. Such disparities may be quite problematic in weak networks or when the share of wind power of the total is large.

There exist various individual or combined strategies to overcome the intermittence of the wind speed. Spatial planning provides some compensation already on a wind park scale but even more so when the geographical range is wider as the air movements become then more heterogeneous. A second strategy is provided by the energy system into which wind energy is integrated – wind energy would then represent an additional variation to the electrical load already being compensated by the production mix. For example in the Nordic context, the joint electricity exchange provides also regulation options to wind power [1]. In case of severe overloading situations limiting the wind power output is possible. A third possible strategy employed for example in remote areas or in micro-grids has been the use of an electricity generation unit in parallel with wind power, for example wind-diesel systems. The option studied in this paper is energy storage in which the storage unit acts as a kind of buffer between the wind production and main network. Depending of the size of the electricity storage available the effects provided could range from mere peak power smoothing into providing more temporarily stable output from wind.

In an earlier paper [2] we have studied how the integration of energy storage with individual wind turbines mainly could smooth out the wind speed fluctuations. Analyzing different types of wind conditions showed that short-term wind power fluctuations could be reduced to half by a storage capacity of 25 kWh per MW wind power. A 3 kWh storage unit could provide a 10% reduction, but in favourable conditions even 1 kWh could do the same. To compensate the fluctuations on a seasonal scale would require a few orders of magnitude larger storage capacity. For example, a 10% reduction in the yearly standard deviation of the wind power output from the average would necessitate 2,000-3,000 kWh storage per one MW wind power. Increasing the smoothing effect up to 30% requires 10,000-15,000 kWh per MW, respectively.

In this paper we extend our previous general analyses on wind-storage systems into numerical energy system modeling to investigate the effects of wind-storage systems in more realistic set-ups. The aim is to find out how storage could reduce some of the adverse power quality effects from wind power fluctuations, in particular on the voltage side. Besides capacity values we also assess the feasibility of different electrical storage concepts to provide the necessary compensation for wind power.

The approach used here is mainly based on numerical and computational simulation of wind power and storage in an electrical network. We use a simulation code called DESIGEN designed at Helsinki University of Technology for investigating the large distributed energy schemes and electrical networks. DESIGN can handle up to 10,000 nodes enabling a realistic representation of load, distributed power generation and electrical network. The model enables to follow the voltage fluctuation in the different parts of the network influenced by the mismatch of load and generation. DESIGEN can, for example, analyze a sub-network (weak) into which wind power and storage are connected which in turn is connected through a transformer into the high-voltage electrical network (strong). Different storage configurations were investigated both in placement (system typology) and size (capacity).

II. WIND POWER FLUCTUATION

A. *Nature of wind power transients*

When estimating the usefulness and demand of energy storage, knowing the time scale of the wind power fluctuations to be compensated is of outmost importance. In earlier work it has been shown that the wind speed contains two distinctive regimes [3]: micro-meteorological fluctuations originating from turbulence and secondly macro-meteorological fluctuations due to major air movements. The time scale of micro instability is typically from seconds to a few minutes whereas the macro region ranges from around ten to over hundred hours.

B. Micro-scale variation

Figure 1 shows an example of the micro-scale power variation in the measured output of a single wind turbine on 1 second time scale over about one hour time scale. (courtesy of VTT, 2001). The example shows that even on a short time scale less than 1 hour the variation in power due to wind speed fluctuations may in practice be tens of percents. This implies that even short-term electrical storage could be most relevant for wind energy systems.

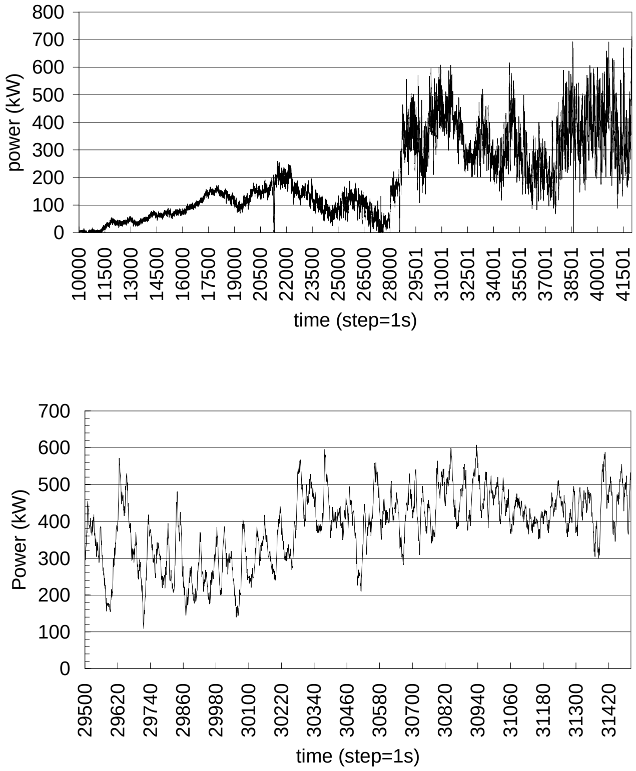
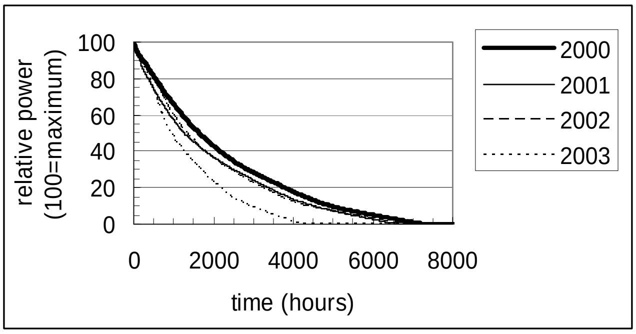


Fig.1. Example of wind power fluctuation on a micro-scale from a single wind turbine using one second measurement interval. Upper: about 10 hours range, lower: about ½ hour range. (courtesy VTT).

C. Medium- and long-term variations

The second example in Fig. 2 shows the yearly power distribution of a single 1.3 MW wind turbine for several years. The wind turbine produces some power for at least 6,500-7,000 hours per year for the 3 years of observations but the operational hours decrease with higher power levels as expected. $P/P_0>80\%$ is clearly less than 10% of all operational time.



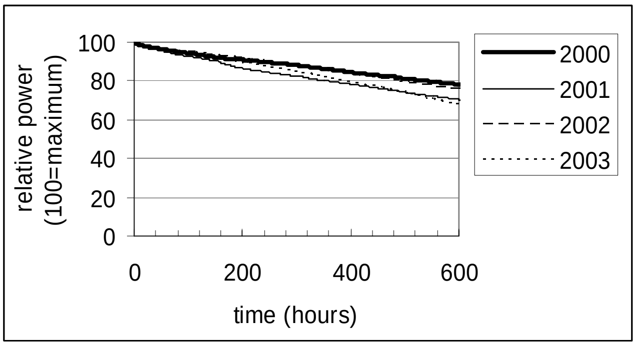


Fig. 2. Measured power duration curve of a single wind turbine (1.3 MW).

As storage is often used to cut-off the highest power output levels, the produced wind energy versus power level is of special interest. In Fig. 3 we show the share of total electricity per year versus the power level of the turbine.
In this case about 60% of all electricity comes at a power level less than 50% of the maximum power rating of the wind turbine.

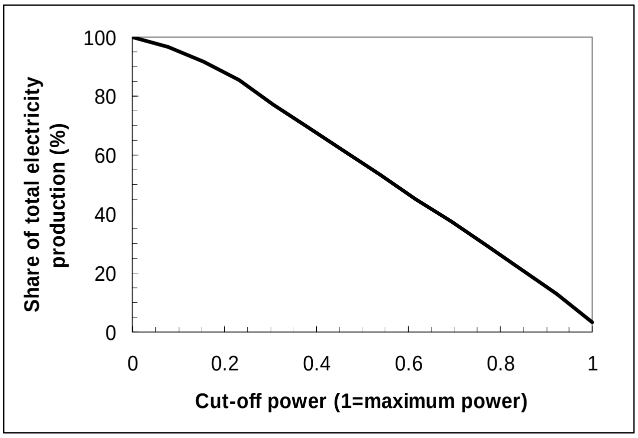


Fig .3 Electricity production at different power levels (1=1.3 MW)

Considering a higher power level, close to one quarter of all electricity comes at 80-100% of maximum power. At a level of 90-100%, still about 10-15% of all electricity will be produced. Fig. 4 illustrates the temporal distribution of the power output at a minimum level of 90% of the maximum power output. The periods of this high power output level typically from less than an hour up to about 10 hours. This gives a crude indication on the required size of the storage to compensate for slightly longer time periods at high wind speeds. From an energy point of view, employing a storage unit at high power levels may therefore be an option instead of reducing or dissipating wind power if constraints would occur on the network side.

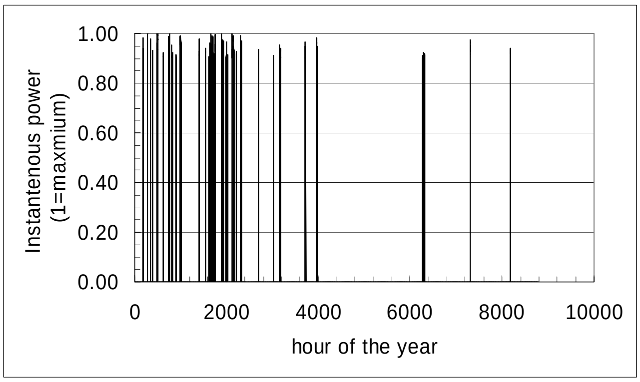


Fig.4. Hourly electricity production at power levels higher than 90% of nominal power. (12% of total yearly production)

III. METHODOLOGY TO ANALYZE WIND-STORAGE SYSTEMS

A. DESIGEN- Simulation model for distributed generation system analyses

The analyses in this paper are done with the DESIGEN simulation tool which has been designed for simulation of distributed energy generation systems. DESIGN is a transient tool that calculates the production, load and power flows/network balance step by step for a given time period [7,8]. The time step is typically from 5 to 60 min. The flow chart of the program is shown below in Fig.5. Different types of network configurations and load profiles can be handled. Typically up to 10,000 network nodes with production, consumption or storage units can be easily handled.

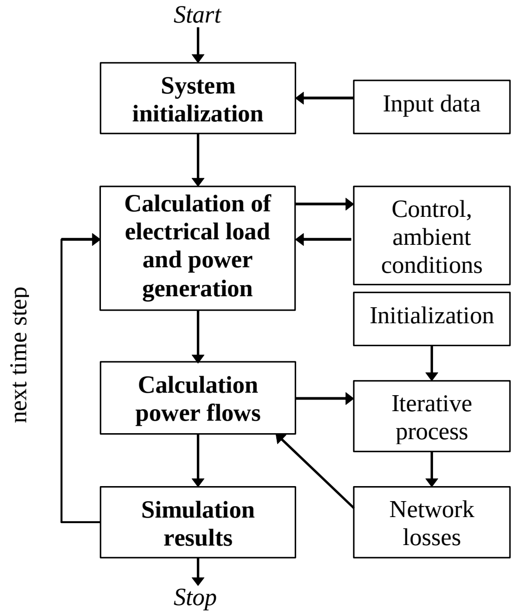


Fig. 5. Structure of DESIGN simulation tool for analysis of distributed generation.

B. System topology

A typical system configuration and network design used in DESIGN is illustrated in Fig. 6. Both distributed generation units and electrical loads can be freely placed into electrical network nodes. The topology, type and length of network/cables are defined in the input.

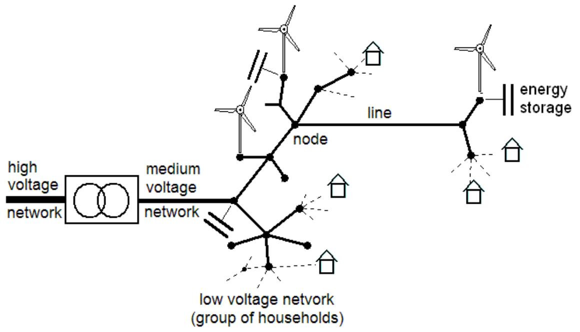


Fig. 6. Illustration of the network with wind generation and storage.

In present study the wind generation units are mainly located in the medium voltage distribution network with a 20 kV voltage level. High-voltage distribution with 110 kV could be an alternative for larger wind shares, e.g. with an own string from the main transmission line.

The placement and capacity of the storage units are an important issue when compensating for the intermittency of wind in the network. Basically wind power integration may influence several features in power quality (e.g. flicker, frequency, harmonics, interruptions, etc.), but here we consider voltage effects only. Voltage is maybe the most critical variable both when considering normal or high quality power. The main function of the storage would be to shave wind power peaks and thus avoid too high voltage levels in the grid. Correspondingly different storage discharge strategies can be defined the simplest being automatic and immediate discharge when voltage drops under the upper allowed level. A more sophisticated strategy would be discharging over a longer time period to minimize overall wind variability. An important design parameter for the wind-storage system is the required capacity versus wind output (MWh/MW)

IV. ELECTRICAL STORAGE TECHNOLOGIES

A. Characteristics of storage technologies

In the next a short overview of possible electrical storage technologies for wind energy applications is presented. The primary parameters of interest are the storage capacity, power level, response time and the cost of the storage unit. Other parameters of interest may be efficiency, physical dimensions, life-time, availability, etc. but these are not considered in this study.

Figure 7 [4,5] shows the main characteristics of different electrical storage systems. Based on their capacity, the storage systems can be divided into short-term and long-term storage. For a single wind turbine, a minimum storage size of relevance on micro-level would be 5-10 kWh/MW and at a MW power level which restricts the available alternatives to battery, fly-wheel or SMES (future technology). On a seasonal level the minimum requirement is a few MWh/MW to see any clear effects which in practice could be met by electrochemical storage systems. The cost is around 100-200€/kW.

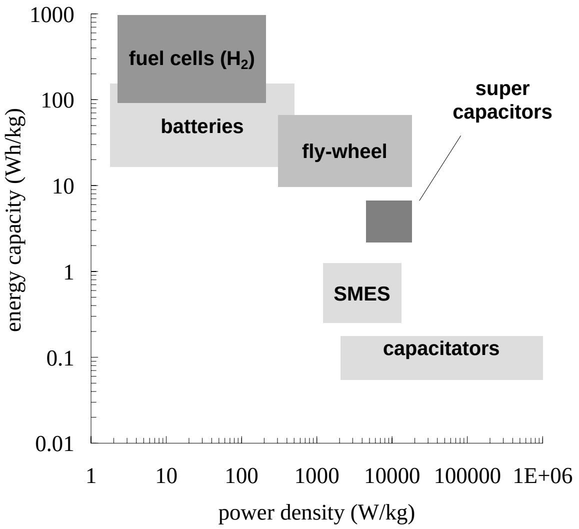


Fig. 7a. Characteristics of short-term electrical storage systems. Storage and power densities are shown.

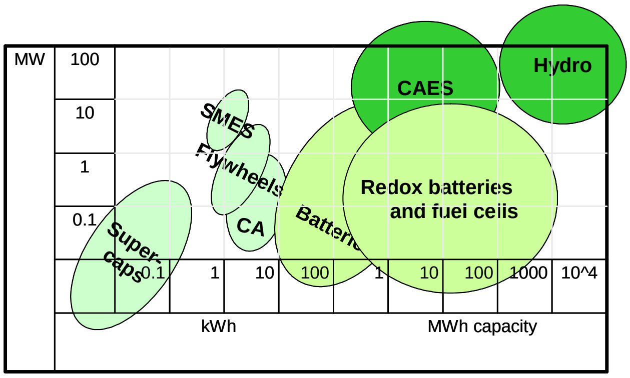


Fig. 7b. Typical capacity and power ranges of different storage systems.

If considering a larger wind park with tens of MW or even hundreds of MW of installed wind capacity, the short-term compensation would require storage from several MWh upwards and seasonal several hundreds to several thousands of MWh of storage capacity, respectively. In this case, hydro power or pumped hydro may provide the traditional solution already employed in electrical networks for fast power adjustments and reserve. For short-term storage only, compressed air storage systems (CAES) could be an option for large-scale storage need. Advanced batteries or reversible fuel cell systems could offer some potential here as well in the future.

A summary of the central technical parameters of promising electrical storage technologies in the wind power context is given in Table 1.

TABLE I
PROPERTIES OF SOME STORAGE TECHNOLOGIES RELEVANT FOR WIND ENERGY

	round-trip η (%)	capacity (MW)	capacity (h)
pumped hydro	80	100...1000	>hours
compressed air	60-75	0.1....1000	< few hours
flywheel	90	0.1-10	0.1
battery	60-80	0.1-10	0.1..>1
flow battery	70	0.1-20	>1
H_2-fuel cell	50	0.1-1	>1

B. Short-term storage technologies

In a capacitor the electricity in the potential difference and electrostatic field between two plates. A supercapacitor is an electrochemical capacitor employing conducting polymers as the electrodes. A supercapacitor enables large power effects per weight having as goal up to 10 kW/kg but a storage capacity around 10 Wh/kg only. The storage time is short or typically up to 30-60 s. A 1 m^3 supercap-storage may yield in the future a 1-5 MW power pulse and weights 100-500 kg [6]. The price is around 200-600€/kW and 50-150 €/Wh but in 5-10 years a price level of 10-15 €/Wh is predicted and a long-term basis the price could drop by a factor of 10-100 by year 2020.

In a flywheel the storage capacity is based on the kinetic energy of a rotating disc which depends on the square of the rotation speed. With light-weighted and strong materials up to a 100,000 rpm frequency is possible. The electricity is discharged by de-accelerating with an electric generator. The flywheel produces high (MW-scale) but short (<15 s) power pulses with a very short response time (ms). The power density may approach even10 kW/kg and the storage capacity 10-100 Wh/kg depending on the material choice and rpm. The investment cost would be around 150-250 €/kW.

In superconducting magnetic energy storage (SMES) electricity is stored into the magnetic field of a superconducting coil presently at a temperature around -269 ^{o}C and in future at a considerably higher temperature when using high-temperature superconductors. The SMES resembles in energy characteristics the fly-wheels and supercapacitors. The storage capacity is some kW-hours but the effect could be several MWs, even tens of MWs. The response time is very short. SMES technology has been demonstrated but the price is still very high.

Batteries are a well-established technology for storage of electricity. The power and capacity are bound together through the electrode surface are meaning that increasing the power level simultaneously increases the storage capacity. The traditional lead-acid battery has an energy density of 20-40 Wh/kg and power density of 20-200 W/kg, for very short times even higher power level is possible. The practical achievable storage capacity depends strongly on the power level used. Largest battery storage facilities 10 MW-scale been constructed in the USA. Future electrochemical battery and fuel cell technologies could increase the performance values well beyond 100 Wh/kg and power densities in the range 100-1000 W/kg. Price level is around 50-250 €/kW.

C. Long-term or large-scale storage technologies

If requiring a large storage capacity or long-term electrical storage, the viable options are just a few. Pumped hydro is a traditional reliable storage and easily incorporated where hydro power is employing large water reservoirs and high heads. The storage capacity is $mg\Delta h$ yielding 0.027 kWh capacity for each ton of water and 10 m elevation. For example a 1000 MWh capacity is obtained with a 100 m head and 370 tons of water.

A second option could be adiabatically compressed air energy storage (CAES) in which gas is compressed with compressors during charging into e.g. a cavern and at discharge released through a gas turbine to produce electricity. Largest CAES realized is in Huntorf Germany with a 300 MW system but a 2000-3000 MW system has been envisioned in Ohio, USA.

An electrochemical storage system in which the electrode surface area and the reactant are separated, e.g. redox systems or fuel cells, could potentially offer a long-term storage option in future.

V. GRID ANALYSIS

Next a parametric analysis on the effects of wind power on the voltage level was done to narrow down the cases where electrical energy storage could provide the best value and largest impacts. We consider here a distribution string connected to the transmission line. The wind power is located at the end of the string. The set-up used is illustrated in Fig.8.

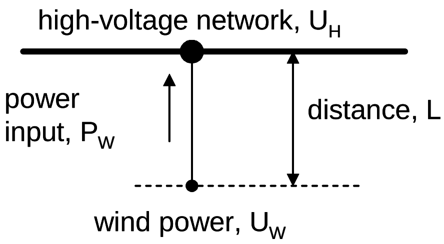


Fig. 8. Illustration of wind power integration.

The network voltage at the wind farm site is U_W and can be calculated from the following formula derived from the basic voltage drop equation in the line:

$$U_W = \frac{1}{2}\left(U_H + \sqrt{U_H^{\ 2} - 4P_W \times (RL + XL \tan\varphi)}\right) \qquad (1)$$

where L=cable length (km), P_W = wind power output, U=voltage, R=alternating current resistance (Ω/km) and X=inductive resistance (Ω/km). For phase angle we use tanφ≈0.2. The voltage loss is the difference between the voltage at the wind farm and high-voltage network.

Figure 9 shows the findings of the analysis for 3 cases.

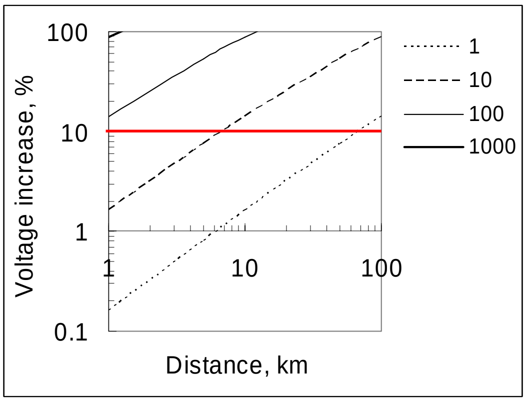


Fig. 9a. 20 kV (Raven ϕ=53.5 mm²) electricity distribution network.

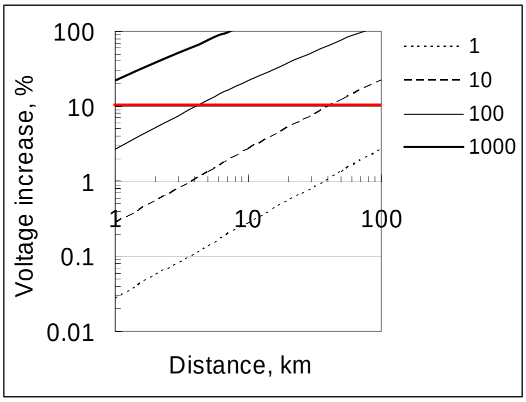


Fig. 9b. 20 kV (Duck ϕ=305 mm²) electricity distribution network

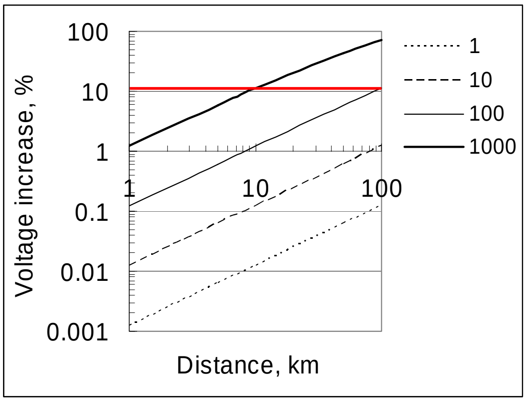


Fig. 9c. 110 kV (ϕ=300mm²) electricity distribution network

The Fig. 9a corresponds to a commonly used cheap 20 kV line (Raven), Fig. 9b is a strong 20 kV line (Duck) and Fig. 9c is a high-voltage 110 kV distribution line. The horizontal axis in Fig. 9 corresponds to the distance of the wind power units from the high-voltage transmission line (440 kV) and vertical axis is the voltage increase at the point of the wind power for a power output of P_W. The parameter shown is the wind power output P_W (1-1000 MW). In rural networks a 10% voltage fluctuation may be acceptable shown by the red line in Fig. 9. The upper limit of the power carrying capacity may in practice be somewhat lower than shown in Fig. 9 due to temperature limitations at high current values.

The high-voltage distribution line is capable of carrying a several hundred MW wind effect at a distance of 10 km within the allowed voltage variation, whereas with the 10 kV Raven the maximum wind power allowed remains at about 6 MW. With the Duck-type 20 kV, 30 MW is the upper limit for a 10 km line with wind at the other end.

The weaker grid alternative is attractive for separate storage units as the wind power level is lower and the required storage capacity for compensation therefore also smaller. In the stronger networks the benefits from the storage are not that pronounced in cutting the overvoltages but in these cases smoothing the feed in power into the high-voltage transmission line may be more useful.

VI. SIMULATION RESULTS

A. *Storage in a linear grid*

As first simulation case we consider a linear 20 kV distribution line typical for rural regions. The length of the line is 70 km and a 4 × 1.3 MW wind farm is connected in the middle of it (node 16, 35 km). The main distribution cable is type Condor with a cross-section of 402 mm². The grid is described by 31 nodes each representing the load of 40 detached houses. The total electrical load is 17,400 MWh/year. The simulation extends over a whole year using a one hour time step.

Figure 10 shows how the wind turbine and storage affects the maximum grid voltage. The minimum voltage experienced in the line is just little affected by the wind or storage. Four alternative places for storage were tried: close to the transmission line (L=0.05), halfway between transmission line and wind turbine (L=0.5) at the wind turbine site (L=1), and at L=1.5. The storage has in this case a capacity of 5,670 kWh (e.g. a battery storage system), or ca 1 MWh per MW of wind.

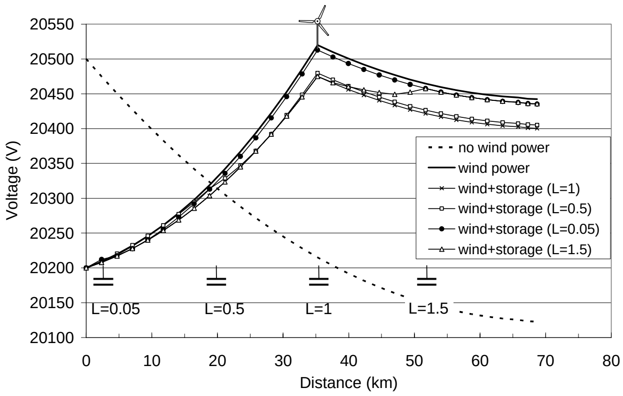


Fig. 10. Maximum voltage along the distribution line.

Locating the storage too far away from the wind turbine downstream does not provide much benefit to voltage smoothing due to the long distance but it should preferably by close to the wind site. In our case having the storage at half-distance provided almost the same voltage reduction at the wind turbine site. Locating the storage half-distance upstream (L=1.5) from the turbine provides a positive effect downstream on the side of the transmission line and is comparable to L=0.5.

The storage capacity of 5,670 kWh used above is able to reduce the maximum voltage level by 10%. If the storage was increased to 54,700 kWh then the decrease is 30%. Putting 2,450 kWh of storage would be able to shave 5% of the peak voltage in this case.

B. *Wind-storage in a sophisticated network*

In the second case a more sophisticated tree-like network configuration was employed shown in Fig. 11. The connection to the transmission line is in node 1. The network branch consists of altogether 78 nodes with electrical loads equal to 11,700 MWh/year. The distribution line is 20 kV. The wind turbines are located in a strong node nr 4 and alternatively in a weaker node 6.

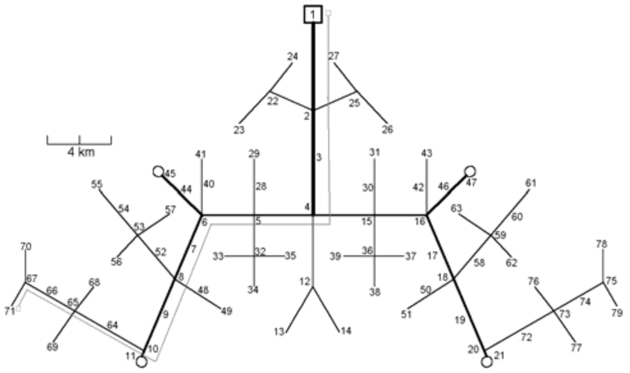


Fig. 11.The network configuration (branch) used in the case simulation.

The lines in Fig.11 consist of different cable types. The distance 1-4 is stronger cable type Ibis (201 mm^2), the main branches e.g. 4-16-21 or 4-6-11 is a Raven (53.5 mm^2) and the last branches e.g. 5-28-29 are type Sparrow (33.8 mm^2). The network offers a challenge to wind power integration due to the network configuration and carrying capacity.

The cases for wind and storage investigated here are the following:

Case	Node	Wind (MW)	Storage (MWh)
1	6	1.3	1.65
2	4	2.6	3.3
3	4	3.9	4.95

First, the voltage fluctuations with wind but without storage are analyzed and then storage is added to reduce the variations. The string voltage fluctuations are tracked in the string between nodes 1-2-3-4-5-6-7-8-9-10-64-65-66-67-71 also shown as a separate line in Fig. 11.

The results of the network analysis are shown in Fig. 12. The minimum voltage in the string is in practice not influenced by the wind-storage coupling but the effects are seen in the maximum voltage level. The benefits of storage are clear in the weak substring (wind in node 6). The storage (capacity is 1.26 MWh/MW) is able to reduce the voltage increase by almost 50% and the voltage variation (min-max) stays within the recommended limits of utilities. Putting the wind into a stronger node causes smaller variation and also the benefits of the storage are much smaller (<10%) albeit same storage capacity per MW of wind.

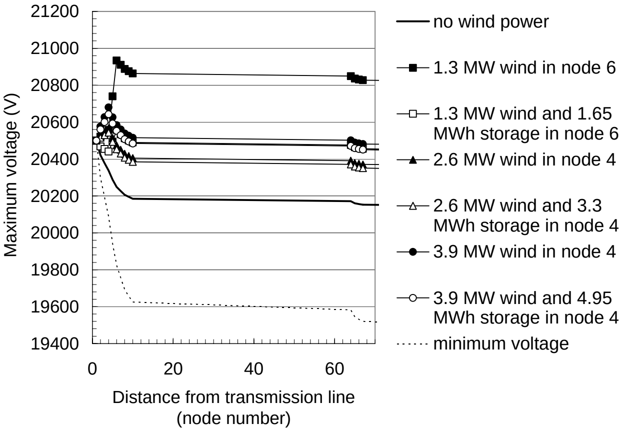


Fig. 12. Maximum voltage in the string of the tree-line network.

Not shown is an additional case in which the wind capacity in node 6 was doubled and the storage as well. The storage is able to reduce in this case 20% of the peak voltage.

VII. CONCLUSION

In this paper the use of energy storage in connection with power has been investigated. The primary interest was in finding the effects of storage on compensating for the voltage increase due to wind power integration.

The study shows that the benefits from storage depend much on the network topology and strength as well as on the amount of wind integrated into the grid. The benefits of storage are larger in weak grids. Using realistic simulation cases showed that in a relatively strong grid the storage with a realistic size may cut the voltage increase from wind by about 10% but in weaker grids the benefits may come up to tens of percents.

The placement of the storage in relation to the wind turbines is also critical to obtain maximum effects. It is recommended to place the storage in the vicinity of the wind turbine either downstream or upstream.

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REFERENCES

[1] H. Holttinen (2005). “Hourly Wind Power Variations in the Nordic Countries”. *Wind Energy, 8.* pp. 173–195.

[2] J. V. Paatero, P.D. Lund (2005). “Effect of energy storage on variations in wind power”. *Wind Energy, 8(4).* pp. 424-441.

[3] J.S. Rohatgi, V.Nelson (1994), Wind Characteristics - An Analysis for the Generation of Wind Power. Alternate Energy Institute: West Texas A&M University, Canyon, Texas, p. 171.

[4] European Commission, “Energy storage – a key technology for decentralized power, power quality and clean transport”, Report EUR 19978, Luxembourg, 2001.

[5] J.P Burton and D.G. Infield, Energy storage and its use with intermittent renewable energy. *IEEE Transactions on Energy Conversion 19(2)*.

[6] Adrian Schneuwly et al. (2004). Ultacapacitors, the new thinking in automotive world. Available: http://www.maxwell.com

[7] J.V.Paatero, P.D Lund (2006). “A model for generating electricity load profiles”. *Energy Research 30 (5).* pp. 273-290.

[8] J.V.Paatero, P.D Lund (2005), “Effects of large-scale photovoltaic power integration on distribution networks”. *Renewable Energy*, accepted for publication.