

Ultracapacitors and Batteries in Wind Power Systems Control and Operation

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Abstract: - In this paper it is studied a feasibility to control a windmill output power with ultracapacitors and batteries. Irregularly varying output power is a typical feature for renewable energy systems. Also wind power includes different types of power variations and breaks that can be a problem for example if a windmill is connected to a weak network. The use of energy storages to control and output power would provide a proper energy management, power quality and improve energy efficiency. The combination of ultracapacitors and batteries makes a commercially available applicable solution to manage both fast and slow changes and breaks.

Key-Words: - Energy storage, Ultracapacitors, Energy management, Wind energy systems, Distributed energy systems.

1 Introduction

Energy storage is seen as a key technology for promoting the wider implementation of distributed energy systems. Distributed generation is often defined as a small-scale generation near the customers including renewable energy, solar and wind generation. Especially wind energy production has been fast increasing. Even if many of the newest wind power investments focus on large wind parks or farms which can be seen more as centralized power production plants, there will be still a lot of stand-alone wind mills and small wind parks that are connected to the local network. A typical feature for all wind power generation is an irregular output with stochastic power variations according to wind variations. Power variations are not usually detectable above normal variations in supply and demand [1], but when the amount of irregularly varied power generation exceeds the performance limits of local network it can influence on power quality and system reliability and increase the need to control output power. Ensuring of the power production reliability, maximum power production control, optimization of power trade and control of island operation are examples of the targets in a longer term power production control that can include both technical and economical aspects.

Different kinds of power variations can be controlled by energy storages [2] starting from very fast variations, which can be controlled by capacitors and superconducting magnetic energy storages up to very slow variations controlled by pumped hydro or compressed air energy storage system.

To provide an ability to smooth fast energy peaks to ensure power quality, and, on the other hand to smooth slower energy variations and manage power production breaks means a combination of fast power storage technology with slower high-energy storage. A currently commercially available, applicable solution for these requirements is a combination of electrochemical (super/ultra) capacitors and batteries.

2 Requirements for energy storages in wind power management

Stochastic power variations are typical for the wind power production. Both reactive and effective output includes large amount of variations in different frequency and amplitude and numerous interruptions of different lengths. Very fast variations ($f > 0.1$ Hz) can be caused by tower shadow effect and fast variations ($f < 0.1$ Hz) by wind gusts. Local variations of wind cause typically minute to hour-level power variations. Long period wind speed variations, time of day, weather, season and maintenance can cause slow (hours) or very slow (days/months) variations or breaks.

Also the system design and control strategy impacts on output power quality. For example fixed speed directly grid coupled asynchronous generator may contribute large reactive power variations and increased voltage variations (flicker). Pitch controlled windmill with a converter on the network connection gives more possibilities to control the output power but on the other hand a converter may increase network harmonics level.

Shutdowns because of too high or low power, faults or maintenance may reduce remarkable produced energy. According to the research made in 12 Finnish wind mills of different types, power and ages, the production break times varied from 1000 hours to 2000 hours per year being 11–22% of yearly maximum production time. Average downtime was about 8 hours. The average output power was 17–28% P_n and standard deviation varied being 26–29% P_n . According to the study of output power variations (kW/s) of

two directly grid coupled asynchronous wind generators fast variations with frequency ≤ 2 s were about 40–60% of the examined variations being about 2% of nominal power (P_n).

Requirements for energy storages in wind power management depend on the time scale and amplitude of the output power variations, desired functions and driving forces such as standards and regulations for example as described in Table 1.

Table 1. Requirements for energy storages in wind power management.

Time scale	Desired function	Driving force	Storage requirements	Energy storage type
Very fast (ms)	Power quality control, smoothing	Power quality standards, regulations, recommendations	Very fast, very high cycle life, power demand varies	Electrostatic/ electro-chemical (super) capacitors, SMES
Fast (s)	Power quality control, smoothing	Power quality standards, regulations, recommendations	Very fast, very high cycle life, power demand varies	Electro-chemical (super) capacitors, SMES, flywheels
Medium fast (min)	Power quality control, smoothing	Power quality standards, regulations, recommendations	Fast, high cycle life, power demand varies	Super-capacitors, flywheels, batteries
Slow (h)	Power smoothing, management of peak power, breaks etc.	Power production reliability, economical aspects	High power, high energy, proper cycle life	Batteries, flow batteries, fuelcell+electrolysator, CAES, pumped hydro
Very slow (d, m)	Energy management	Power production reliability, economical aspects	High energy and power	Batteries, flow batteries, fuelcell+electrolysator, CAES, pumped hydro

CAES (Compressed Air Energy Storage), SMES (Superconducting Magnetic Energy Storage)

The control of short time variations is typically based on standards, regulations and recommendations for network power quality. That includes regulations for voltage and frequency levels, reactive power, transients and harmonics. Ensuring of the power production reliability, maximum power production control, optimization of power trade and control of island operation are examples of the targets in a longer-term power production control.

Despite the active research and development, which is going for all areas of energy storage, any of the current energy storages cannot fulfill the demand of fast, long life, high energy and high power storage system. Combination of fast power storage technology with slower high energy storage will provide for example an ability to smooth fast energy peaks to ensure power quality, and, on the other hand, to smooth slower energy variations and manage power production breaks. A commercially available solution, which is already implemented in hybrid electric vehicles [3], is a combination of electrochemical (super/ultra) capacitors and batteries. Most commonly used batteries in stationary applications are still lead acid batteries. Modern closed types of lead acid batteries need less maintenance and have longer life cycle. Electrochemical capacitors are small-sized and nearly maintenance-free. They have long cycle-life (up to 1 million cycles) and high power density (10 kW/kg) being suitable to smooth fast high power peaks. Electrochemical capacitors combined with batteries will give a more efficient system decreasing the amount of batteries and their charge/discharge cycles and providing better possibilities to manage high amplitude and high frequency variations of power.

3 Case study of the control wind power systems with ultracapacitors and batteries

There are two basic concepts to connect a dual storage system (DC-sources) to a wind turbine concept. In Fig. 1 a) there is a directly grid coupled asynchronous generator and the storage system is connected to the generator output before a network transformer. In Fig. 1 b) the storage system is connected into the DC-link of the windmill network converter.

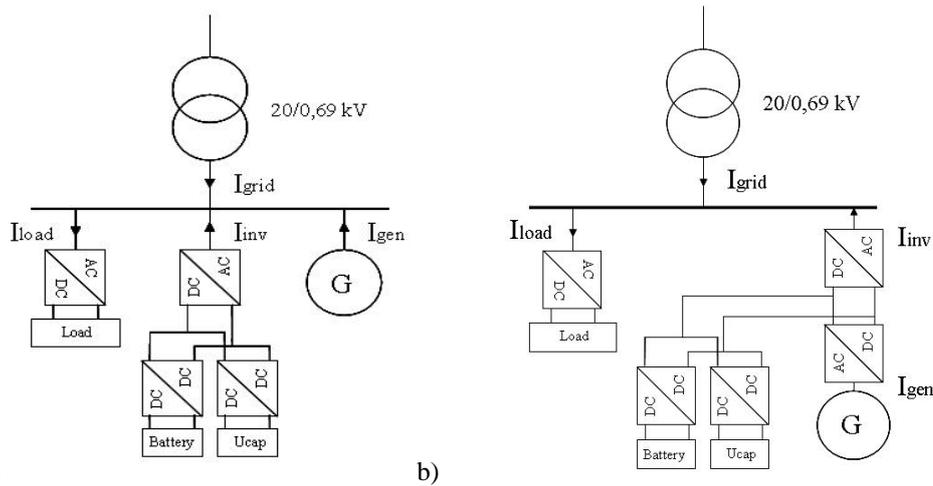


Fig. 1. Energy storage concept to control the output of a) a directly grid coupled wind power generator and b) variable speed wind power system.

Electrochemical capacitors can be used in these concepts to control automatically the short-term power changes for example to avoid power quality problems such as flicker. A battery bank can be controlled according to many different aspects such as to limit maximum output power, to sustain minimum output power, to smooth output power, to maximize profit from electricity trade and to support load management e.g. peak shaving. The storage system substitutes reactive power compensation capacitors. Both concepts are usable also in the other solutions of the distributed power generation and use.

In this paper it is presented a simulation study where feasibilities to smooth the output power of the 1 MW (690 V, 50 Hz) directly grid coupled wind mill is examined using concept presented in Fig. 1. The wind power generator is a fixed speed asynchronous type. The data (kW/s) used in simulations is measured from a 1 MW windmill located on the west coast of Finland. The dual energy storage is the combination of ultracapacitor and lead acid battery banks. In addition to the battery and ultracapacitor banks, the main parts of the storage system are DC/DC-converters, DC-AC-converter and power electronic control circuits. The simulation system is built by the PSCAD/EMTDC software.

Both full-bridge DC-DC-converters are isolated and bi-directional. Electrical isolation is implemented by using a transformer between the LV-side and HV-side of the converter. DC-DC-converters are operated on the boost mode (discharging mode), when power is fed from storages to the DC-AC-converter DC-bus, and on the buck mode (charging mode) when power is absorbed from DC-bus. In the boost mode, control circuits of DC-DC converters match the output voltage to the DC-bus of the inverter. In the buck mode, charging current is limited to the suitable level for energy storages.

DC-voltage is converted into AC-mode by using a three-phase, current controlled inverter that sets the voltage and the frequency suitable for the power grid. The inverter can also operate in the discharging and charging mode. The modulator of the inverter is implemented by using a Space Vector Theory. Technical specifications for the power electronic devices, ultracapacitors and batteries are listed in Table 2.

Table 2. Technical specifications for the power electronic devices and storages.

DC-DC		DC-AC		Ultracapacitor		Battery	
$V_{\text{primary}} (\text{Vcap})$	700 V	V_{dc}	1050 V	V_n	2.7 V	V_n	2.0 V
$V_{\text{primary}} (\text{Bat})$	500 V	$V_{\text{out}} (3\text{-p})$	690 V	Capacitance	1700 F	Capacity	1500 Ah
f_{sw}	3 kHz	f_{sw}	3.6 kHz	Number of cells in series	259	Number of cells in series	250
				Rated current	371 A	Max. charge current	200 A
						Max. discharge current	4000 A

3.1 Wind mill output power smoothing

Utilization principle of the energy storage system

The main purpose of the energy storage system is to adjust the output power of the wind power generator. Fast and mainly small changes are eliminated with ultracapacitors. Slow and mainly big changes are adjusted with batteries. Energy storages have different kind of control methods. Fig. 2 presents operating areas for batteries and ultracapacitors. When output power is higher than upper setting value P_{set_upper} , batteries are charged. Correspondingly, if power is less than lower setting value P_{set_lower} , batteries operate in the discharge mode. When the output power is between these two power limits, ultracapacitors are charged or discharged.

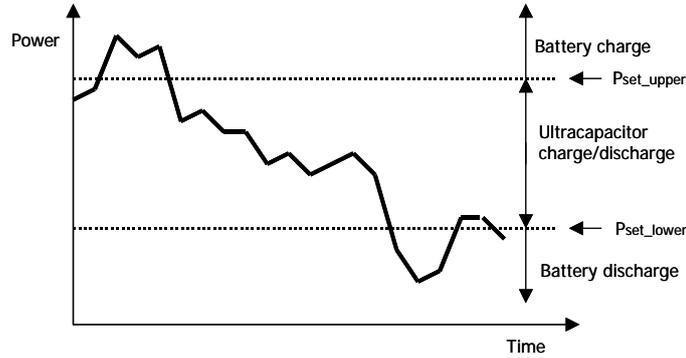


Fig. 2. Operating areas for batteries and ultracapacitors.

Control method and simulation results

A battery is modelled as a voltage source V_b in series with a variable resistance R_b and a simplified model for an ultracapacitor consists of a series connected capacitor C and an internal resistance R_c (Fig. 3). The battery resistance is a function of state of charge (SOC) and defined on the basis of the product data. SOC for battery and for ultracapacitor is calculated by using the equations (1):

$$SOC_{battery} = 1 - \frac{Capacity_{used}}{Capacity_{max}} \quad SOC_{ultracapacitor} = \frac{V_{out} - V_{min}}{V_{max} - V_{min}} \quad (1)$$

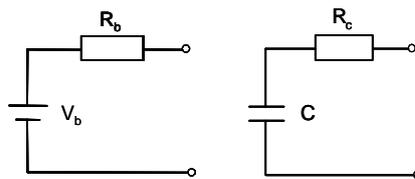


Fig. 3. Equivalent circuit for the battery and ultracapacitor.

In these simulations, the following parameters are used: P_{set_upper} is 900 kW and P_{set_lower} is 350 kW. Power fed from batteries to the utility grid is controlled so that the grid power is kept at least in the value of 350 kW (P_{set_lower}). Fig. 4 a) shows the simulation results. The ultracapacitor bank is controlled by an estimation method based on the moving average value of latest samples of the measured power data and SoC of capacitors. Fig. 4 b) presents simulation results, when ultracapacitors are used to smooth short-term power fluctuation.

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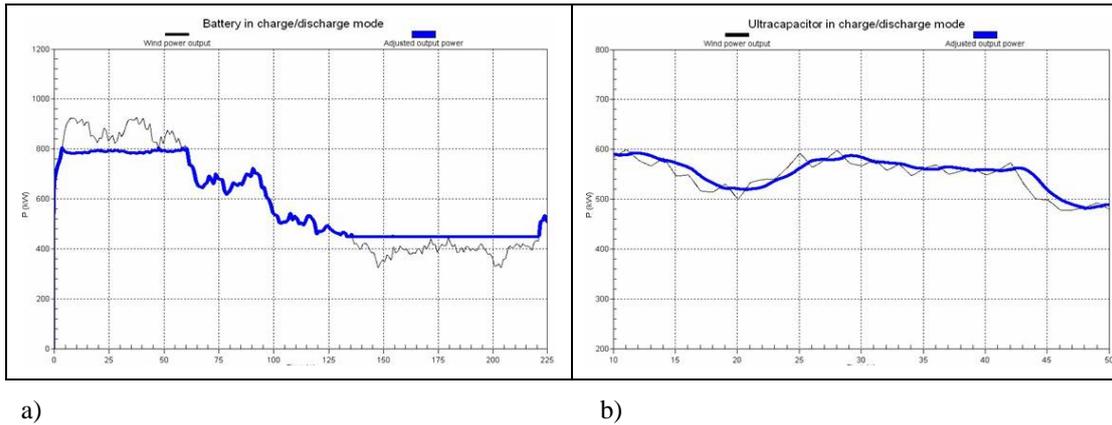


Fig. 4. Power smoothing by a) battery and b) ultracapacitors.

3.1 Harmonic current reduction and reactive power compensation

Simulation case study concept (Fig. 1) included harmonic current source connected to the windmill output. Using static shunt compensator method [4] energy storage system can compensate the load current harmonics and the reactive power. Simulation results of active filtering can be seen in Fig. 5.

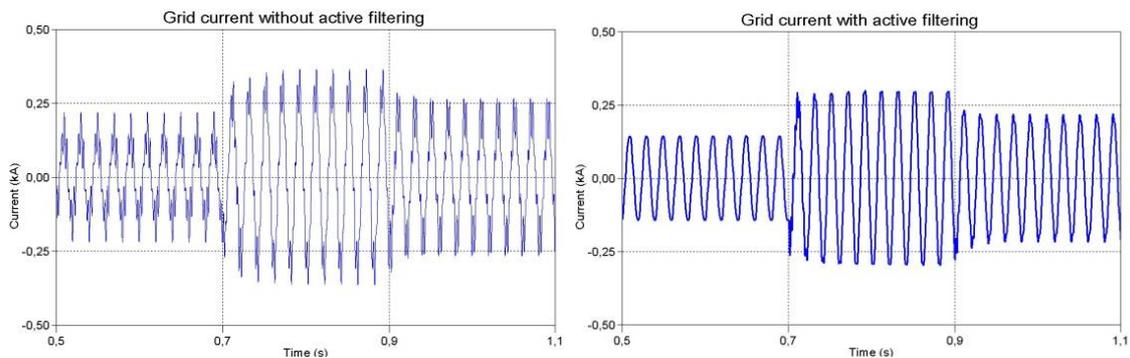


Fig. 5. Grid current without and with active filtering. (0.5s-0.7s storage is in charge mode, 0.7s-0.9s in discharge mode, 0.9s-1.1s no storage function).

Simulation results for reactive power compensation can be seen in Fig. 6 where P_{inv} is real power and Q_{inv} is reactive power coming from storages, Q_{gen} is reactive power to wind generator, Q_{load} is reactive power to load and Q_{grid} is reactive power needed from grid and controlled here by storages to zero.

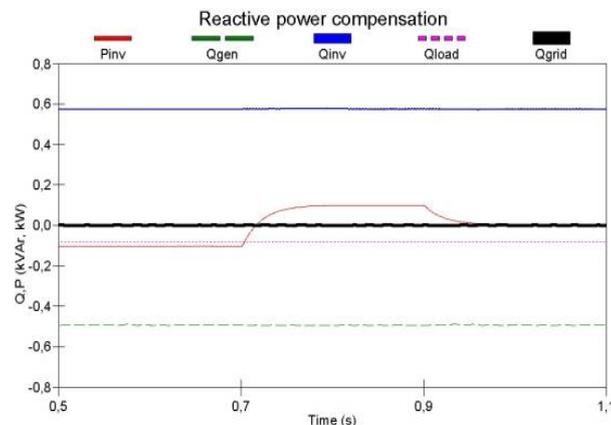


Fig. 6. An example of the reactive power compensation by using ultracapacitors and batteries. (0.5s-0.7s storage is in charge mode, 0.7s-0.9s in discharge mode, 0.9s-1.1s no storage function).

4 Conclusion

In this paper it has been presented the feasibility of the use a combination of ultracapacitors and batteries to maintain power quality, control reactive power, compensate harmonic currents and smooth both fast and slow changes of the wind mill output power. The simulations of the wind generator output power smoothing have been done using an ultracapacitor-battery storage system and measured output power data from a fixed speed asynchronous wind generator. By the combination of ultracapacitors and battery, the ability to smooth both fast and slow changes of the output power has been achieved. The lead acid battery bank was charged when the generator output power was over the upper limit and discharged under the lower power limit. Using ultracapacitors to smooth fast and mainly small changes, which could affect e.g. voltage variations (flicker) on weak electrical grid, we can also increase the life of batteries decreasing charge/discharge cycles and decrease the size of battery system eliminating the need to overcharge battery for longer cycle life. The simulation concept included also nonlinear load, which generate harmonic currents. Harmonic current was compensated by the storage system. A fixed speed asynchronous wind generator takes reactive power from grid and needs typically separate capacitors to compensate that. Energy storage system gives a possibility to compensate and control the reactive power, which the wind generator and here also the nonlinear load takes from the grid. The described energy storage system with interconnection to DC or AC network is usable also in the other solutions of the distributed power generation and use.

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