Overview of the Energy Storage Systems for Wind Power Integration Enhancement

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***Abstract*-As the installed worldwide wind energy capacity increases about 30% annually and Kyoto protocol that came in force in 2005, wind penetration level in power system is considered to significantly increase in near future. Due to increased penetration and nature of the wind, especially its intermittency, partly unpredictability and variability, wind power can put the operation of power system into risk. This can lead to problems with grid stability, reliability and the energy quality.**

One of the possible solutions can be an addition of energy storage into wind power plant.

This paper deals with state of the art of the Energy Storage (ES) technologies and their possibility of accommodation for wind turbines. Overview of ES technologies is done in respect to its suitability for Wind Power Plant (WPP). Services that energy storage can offer both to WPP and power system are discussed. Moreover examples of already existing installations are shown.

***Index Terms*-Wind Power Plant (WPP), Energy Storage (ES), Transmission System Operator (TSO).**

I. Introduction

In the past decades the generation of electricity was mostly based on fossil fuels and atomic energy. However in recent years the environmental concern and continuously growing price of energy from fossil fuels was one of the reasons for the rapid growth of wind energy as a clean and inexhaustible energy source all around the world [1], [2].

According to newest data from World Wind Energy Association (WWEA), even in the year 2009 which is the year of global financial crisis, the total installed capacity worldwide will reach 152 000 MW by the end of 2009 [3]. This means that in 2009 there will be 30 300MW of new installed capacity what corresponds to 25% growth in comparison to previous year (Fig.1).What is more, according to the report of The European Wind Energy Association (EWEA), year 2008 in the EU was the first year in which more wind power was installed than any other electricity generating technology, (Fig.2) [4]. In 2008 in EU 8484MW of new wind capacity was installed, beating all other power technologies like coal, gas, and nuclear power. As the recently set ambitious European plans for future shares of renewables, the growth of wind power can be expected to continue [5].

However further wind energy integration to power system encounters many new challenges. One of them is the fact that inherent variability and partly unpredictability of wind cause

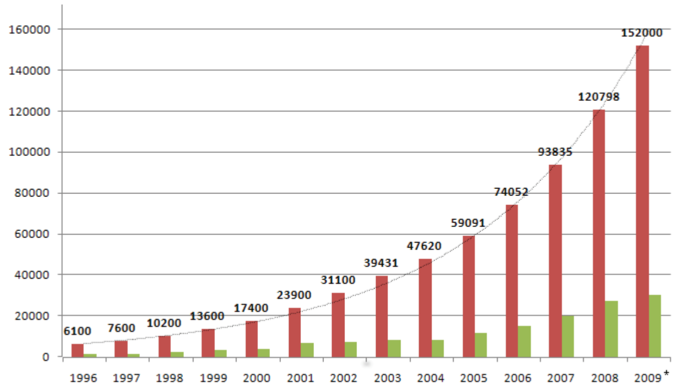

Fig. 1. Global accumulative (red) and global annual (green) installed wind capacity. (2009* predicted value).

power fluctuations in the system that can be even more difficult to manage than load variations including load-forecasting errors [5]. Wind power increases the need for the regulation of power and requires reserves in the minute to hour timeframes [6]. It increases the integration cost of wind power because reserves are often provided by conventional generating units [7], [8]. Generally, the greater the wind power penetration into the power system is, the bigger reserve power is needed in order to balance the grid during weak wind conditions [9]. The U.S. Department of Energy estimates that, for every GW of wind capacity added, 17 MWs of spinning reserves must also be built to account for the system's variability [10]. What is more, the best wind resources are often found in rural areas far from existing high capacity transmission lines [11]. One of the actions that can be taken to decrease wind power fluctuations and variability and allow further increase of wind penetration in power system can be an integration of energy storage technology with Wind Power Plant (WPP).

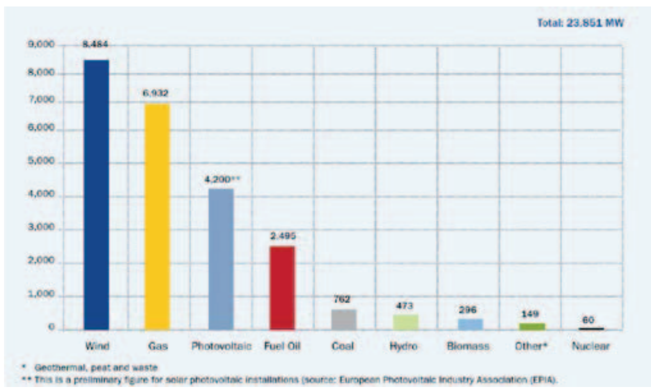

Fig. 2. Newly installed power capacity in EU, 2008 [4].

Energy storage has already wide variety of applications like supplying power to portable devices, UPS and recently in hybrid cars to reduce fuel consumption, etc. However, addition of energy storage technology to WPP is not a good explored area yet.

In more recent times, the complementarities between storage and renewables has become of particular interest, both in terms of capturing enhanced value from such essentially intermittent resources and in maintaining stability in the electrical power system [12].

This paper makes a review of energy storage technologies in respect to suitability for wind power fluctuation suppression. In part III potential applications of ES are illustrated and requirements for each application are stated. Part IV assigns technologies to applications and is followed by examples of actually existing installations of WPP with ES.

II. Overview of Energy Storage Technologies

Energy storage has the greatest potential to solve many wind integration issues [13]. However, ES technologies are having different potential and are on the different stadium of development.

Electrical energy can be stored in form of different kind of energies: mechanical, electro-chemical, electromagnetic, thermal. Fig. 3 presents a classification of energy technologies.

Short description of energy storage technologies and their possibility of accommodation for wind power is further presented in this paper.

A. Pumped Hydro Energy Storage (PHES)

It is the largest and the most mature technology available [14] with about 300 systems operating worldwide [15]. PHES consists of two reservoirs and body of water at a relatively high elevation represents potential or stored energy [15]. The principle of operation is simple and during energy production it is similar to hydroelectric power plant. During the "charging" process water from lower reservoir is pumped up to the upper one. In "discharging" process water from upper reservoir is released and flows through hydro turbines which are connected to generators, producing electrical energy [16].

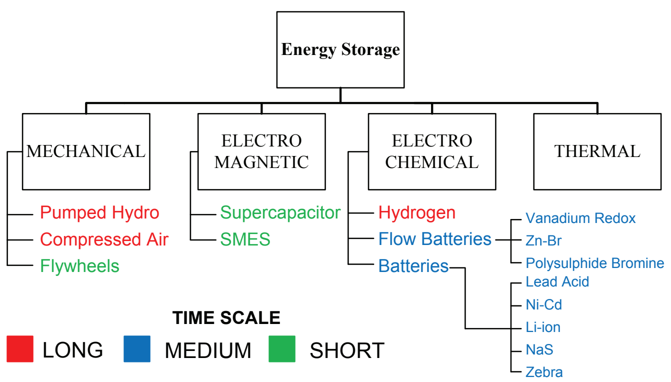

Fig. 3. Energy storage technologies classification

In case of hydro power plant pumping is irrelevant. In most cases the hydro facility could be used as storage without any pumping because it has a supply of water from a river. So simply reducing the output from the hydro facility is equivalent to "charging" the storage with practically 100% of efficiency.

Wind farm support possibilities:

PHES is a good solution for wind farms. Ideal application for PHES seems to be load leveling [14].

One of the problems for building these stations is the lack of suitable places and the impact in the nature environment [17]. Relatively new approach which can give more deployment flexibility is Underground Pumped Hydroelectric Energy Storage (UPHES). This gives a flexibility of UPHES location what in consequence this technology can be placed in ideal locations to function with wind farms [14]. However, the problem is very high technical immaturity of UPHES.

Hydro power plants are one of the best storage solutions for suppressing fluctuations caused by WPP.

B. Compressed Air Energy Storage (CAES)

CAES is also a quite old technology; however the number of installations in the world is just two [18]. CAES systems are compressing air via electrical compressors in underground cavities (salt cavern, abandon mines, rock structures etc.) and store it in a high pressure. When energy is needed compressed air is released through a turbine, but the operating units worldwide incorporate combustion prior to turbine expansion in order to increase the overall efficiency [16], [18].

Wind farm support possibilities:

High power and energy capacity make CAES a good storage solution for wind farms. CAES can be used for frequent start-ups and shutdowns. Current research in CAES is focused on the development of systems with fabricated storage tanks. Such an approach will remove the geological dependency and compressed air will be stored in tanks with a higher pressure. System rating will be smaller (several MW) because of the tank cost. The possible lack of geological dependence might make CAES an interesting solution for integration with wind farms [19].

C. Flywheel Energy Storage (FES)

Flywheels are energy storage devices which are storing energy in form of kinetic energy (rotating mass). Flywheels are made up of shaft that rotates on two magnetic bearings in order to decrease friction [14]. Whole structure is placed in a vacuum to reduce windage losses. The principle of operation is simple. During 'charging' process rotor is accelerated to a very high speed by a motor and energy is maintained in a system as kinetic energy [14]. In 'discharge' process flywheels are releasing energy and driving the machine which is working now as a generator.

Wind farm support possibilities:

Flywheels are not very well suited for wind farm support. They are able to suppress fast wind power fluctuations but with a small time scale. They can be considered as a support for wind turbines in combination with battery system rather than stand alone. However energy density is low and moreover self discharge ratio is high. Unerco Power Technologies has demonstrated the application of kinetic energy storage to the smoothing of the output of wind turbine systems [12].

Most of current research is focused on high speed flywheels which are able to rotate with a speed even up to 100 000 rpm.

D. Supercapacitor Energy Storage (SES)

In SES energy is stored in electric field. Principle of operation is the same as in conventional capacitor; however supercapacitors use polarized liquid layers between conducting ionic electrolyte and conducting electrode to increase the capacitance. Due to the fact that capacitance is dependent also on the surface area of electrodes, highly porous material is used in order to increase the area [16]. Supercapacitors can be rated even up to 5000F.

Wind farm support possibilities:

SES are having similar response characteristics and small energy density like FES but they do not have moving parts and are having small self discharge ratio. They are able to suppress fast wind power fluctuations but with a small time scale. They can be considered as a support for wind turbines in combination with a battery system rather than stand alone.

E. Superconducting Magnetic Energy Storage (SMES)

SMES stores energy in magnetic field. SMES consists of superconductive coil, power conditioning system, refrigerator and vacuum [14]. Magnetic field is produced by DC current circulating through a superconducting coil [16]. In order to get rid of the resistive losses caused by current flow, the coil is kept in superconducting state. Cooling medium is liquid helium or nitrogen.

Wind farm support possibilities:

SMES are unlikely to be used for integrating renewables [14]. Superconductive coil is very sensitive for temperature changes; moreover SMES has small energy density and power capacity up to 2 MW. SMES is now usually utilized in industrial power quality market.

F. Lead Acid Battery Energy Storage (LAES)

It is the most mature (research over 140 years) and the most commonly used battery storage technology at present [16], [14]. There can be distinguished two kinds of lead acid batteries: flooded (FLA) and valve-regulated (VRLA). FLA batteries are constructed from two lead plates which are immersed in a mixture of sulphuric acid and water. In case of VRLA batteries the operational principle is the same; however they are sealed with a pressure-regulating valve which prevents venting of the hydrogen and eliminates the air from the cell. VRLA are having higher initial cost and shorter lifetime, however they have an advantage over FLA in smaller weigh, volumes and lower cost of maintenance.

Wind farm support possibilities:

LAES can be considered as a support of wind power. There exist stationary application of LAES in the world rated in MW for power system applications; however LAES usually lose with other batteries when it comes to wind power integration, mainly because of smaller power density, low depth of discharge, life cycle capability and extreme sensitivity to temperature changes. Also depth cycles are decreasing the life time of LA batteries.

Currently effort is put in research of LA batteries that can be charged in minutes [14]. It is rather unlikely that this technology will be playing important role in a future as a large scale storage device, mainly due to very limited number of cycles. Moreover, an interesting solution seems to be also ultra battery which is LAES with integrated supercapacitor in one unit cell developed by CSIRO. Ultra battery can provide high power discharge and charge with a long, low-cost life [25].

G. Nickel Cadmium Battery Energy Storage (NCES)

Nickel Cadmium is a mature solution similar like a LA batteries [18]. NCES consists of positive electrode (nickel hydroxide) and negative one (metallic cadmium). Electrodes are separated by nylon divider and aqueous potassium hydroxide is the electrolyte. During discharging process nickel oxyhydroxide reacts with water and produces nickel hydroxide and a hydroxide ion. At the negative electrode cadmium hydroxide is produced. During charging process of the battery process is reversed.

NiCd batteries can operate in wider temperature range in comparison to LA. If NiCd batteries are operated with small depth of discharge, then they are able to achieve much more cycles.

Wind farm support possibilities:

It is rather unlikely to use this technology for WPP purposes [14]. It exist a possibility of total ban of NiCd batteries by European Commission [16]. Life span of NiCd batteries can be significantly reduced for a deep cycles. What is more this technology suffers from memory effect. Other problem is the environmental impact of the technology. Cadmium is a toxic heavy metal and there are concerns related to disposal.

H. Lithium Ion Battery Energy Storage (LIES)

This technology was first commercially available in 1990 [16]. The cathode is lithiated metal oxide while anode is graphic carbon with layer structure [26]. The electrolyte is a lithium salt in organic solvent. In this case during discharging lithium migrates from anode to cathode. During charging reverse process occurs. The weight of LIES is approximately one half compared to NCES of similar capacity and volume is 40 to 50% smaller than NCES [27].

Wind farm support possibilities:

This technology can be sized in MW and therefore become a serious player in large scale applications. LIES seems to be relevant for WPP. Characteristic feature of this technology is small weight, high efficiency and high cell voltage and power density. LIES can be shaped into a wide variety of shapes and sizes. Moreover this technology does not have a memory effect. Other features are small self discharge (0.1% per month) and long life for deep cycles. It is likely that LIES performance will be significantly improved because of a lot of research is done especially in respect to electric cars.

I. Sodium Sulphur Battery Energy Storage (NaSES)

Sodium Sulphur batteries became commercially available in 2000. The cell is usually constructed in a tall cylindrical configuration. Positive electrode contains molten sulphur and negative electrode from molten sodium [14]. Electrolyte in this case is solid β-alumina. Thus, during discharging of the battery, sodium ions pass through electrolyte and combines at positive electrode with sulphur, creating sodium polysulfide. In charge process reaction is reversed.

NaSES battery can be classified to group of high temperature batteries. Because sulphur has to be kept in liquid form, cell has to operate in temperature range 320-340°C.

If cooled down when not fully charged, the batteries will suffer serious damage. Due to this a diesel genset is often implemented together with a NaSES installation, in case of power outage.

<u>Wind farm support possibilities:</u>

This technology can be sized in MW and therefore it can become a serious player in large scale applications. NaSES seems to be relevant for WPP. There are currently working applications of NaSES with WPP.

Characteristic feature in NaSES is high energy density (three times higher in comparison to LAES) [14]. What is more NaS batteries are able to deliver power in single continues mode as well as large short pulses. NaSES are capable to survive much more cycles in comparison to LA batteries. Cost of NaS batteries now is relatively high, however it is considered to drop with a mass production because these batteries are constructed from inexpensive, abundant and recyclable materials [14].

Currently however there is only one manufacturer of NaSES batteries, NGK Insulators in Japan.

J. Sodium Nickel Chloride Battery Energy Storage (ZEBRA)

Sodium Nickel Chloride battery, popularly called ZEBRA are belonging to the family of high temperature batteries. Negative electrode consists of liquid sodium (like NaS) but positive electrode is nickel chloride. Also β- alumina electrolyte is used but in addition there is a second liquid electrolyte (sodium chloroaluminate) which is used to allow fast transport of sodium ions form the solid nickel chloride electrode to and from ceramic electrolyte [20]. The best performance of a cell is achieved for the temperature range 250-350 °C.

<u>Wind farm support possibilities:</u>

ZEBRA batteries are able to play a role in the future in integration of renewables. However, right now ZEBRA batteries aim mainly in e-mobility. This technology is characterized by high energy density (5 times higher than LA). They are resistant for short circuits. What is more in comparison to NaS, Zebra batteries are able to survive certain overcharge and discharge and have a better safety characteristics and a higher cell voltage [16].

K. Flow Battery Energy Storage (FBES)

There can be distinguished following three kinds of flow batteries: Vanadium Redox (VR), Polysulphide Bromide (PSB), Zinc Bromine (ZnBr). Flow batteries principle of operation differs from conventional batteries. Energy is stored as a potential chemical energy by means of reversible reaction between two electrolytes. Energy is stored in the electrolyte solutions. This makes the power and energy capacity decoupled. The size of the cell stack determines the power capacity, while the volume of electrolyte determines energy capacity [16]. Two charged electrolytes are pumped to the cell stack. In the cell stack a chemical reaction occurs [14]. For each technology charge to discharge ration is 1:1 and batteries do not suffer from depth discharge.

Operation of Polysulphide Bromide (PSB) is similar to VR. Characteristic feature is very fast reaction time. PSB batteries can be used for frequency response and voltage control. The disadvantage is the fact that small quantities of bromine, hydrogen and sodium sulphate are produced what imposes some maintenance [14].

In case of Zinc Bromine (ZB) technology, operation principle is different than in previously mentioned VR and PSB batteries, however it contains the same components. During process of charging the electrolytes of zinc and bromine ions flow to the cell stack. The electrolytes are separated by a microporous membrane. The difference is that electrodes in a ZnBr flow battery act as substrates to the reaction. As the reaction occurs, zinc is electroplated on the negative electrode and bromine is evolved at the positive electrode (similar to conventional battery operation).

<u>Wind farm support possibilities:</u>

This technology can be sized in MW and therefore it can become a serious player in large scale applications. FBES seems to be relevant for WPP. There are already existing applications of VR with WPP.

L. Hydrogen Energy Storage (HES)

Hydrogen energy storage is one of the most immature technologies [14]. Hydrogen electric energy storage is not a single device but the process is divided into three parts:

- create hydrogen
- store the hydrogen
- create energy from hydrogen

Hydrogen can be created by: extraction of fossil fuels, reacting steam with methane and by electrolysis. Producing hydrogen from electrolysis is the most economical solution among the others. Production from fossil fuels is four times more expensive than using the fuel itself [14]. And production of hydrogen from reaction of steam with methane produces pollution. During the process of electrolysis, hydrogen is produced from water and oxygen is dissipated into atmosphere. Latest advances increased the efficiency of hydrogen production to 85%. Storing of hydrogen can be done by compressing it, by liquefying it or by metal hydride [14].The most often use option is to compress hydrogen (65-75% efficiency). Hydrogen can be also stored in liquefied form by pressuring and cooling it. However keeping the hydrogen liquid is energy demanding because of the very low temperature that has to be maintained.

To create energy from hydrogen two methods are used: Internal Combustion Engine (ICE) and Fuel Cell (FC).

Round trip efficiency is between 30-50%.

Wind farm support possibilities:

Fuel cell is relatively new technology and do not have any moving parts, no emissions, are light and reliable. Hydrogen has a higher energy density per weight but lower per volume than a gasoline. These features give a lot of potential in a future, also with renewable applications however technology needs to be more advanced.

Comparison of ES technologies can be found in Table 1.

III. Applications of Energy Storage for WPP and Grid Support

Operation of ES as a part of WPP can not only reduce power fluctuations but also enable introduction of WPP into new markets. WPP characteristics can be made even more like conventional power plants.

The challenge of wind power resources integration is not a significant issue as long as the penetration rates are small, typically <10%. As penetration increases and becomes >20%, of the load, there is required added regulation and spinning reserve resources to assure grid stability control. What is more, increased wind generation might reduce the regulation capability of the control area by displacing other generation units (usually the less economical ones). Grid operator may mandate that all the wind generators have to meet certain stability requirements as a condition for grid access [21].

Energy storage systems can be applied to the wind resource in order to provide all or some portion of the additional regulation control and spinning reserves [21].

Services that energy storage can offer for grid and WPP can be classified as follows:

- Imposed by grid codes
- Ancillary services (not required by TSOs)

A. Applications imposed by grid codes

Grid frequency support

The purpose is to suppress fluctuations of the frequency in a grid which have a source in imbalance between generation and load [21]. In grids with high wind penetration, sudden reduction of wind power can contribute to frequency drop. It is possible to support grid frequency without energy storage in certain range by utilizing droop control and rotor inertia. With ES, frequency can be controlled without any curtailments of wind power.

Production predictability (forecast improvement)

The predictability of the production from a WPP depends on the quality of the weather forecast and of the service forecast [11]. Forecast accuracy is dependent on time scale, site and season. In some countries forecast is required, however there are rarely any penalties if forecast is incorrect. In other markets, like Spain, there are penalties imposed on wind energy suppliers when generation does not match amount of generation bid for delivery [21].

There is usually a need for forecast with 15min resolution. Production predictability can be improved (in consequence penalties decreased) with ES which can compensate to some extend unforeseen changes in the wind [11]. This service requires that wind energy in excess of bid amounts is stored and released when the amount of wind power is insufficient.

Inertia

Inertia emulation is mentioned in the new draft of Spanish grid code as a future requirement for a WPP connected to the grid [22]. Typically value of inertial constant for wind turbine is dependent of the mass and is in range of 4-9s. Increased inertia in a grid reduces frequency variability and makes the grid less sensitive to sudden load and/or generation changes. Addition of ES can significantly increase the apparent inertia of WPP.

Oscillation damping

It is also a new future requirement that can be found in [22]. If no disturbance is present, relative angular positions of synchronous machines rotors remain constant. Sudden or significant changes of power flows in an interconnected transmission system some machines can loss synchronism. This service require that power oscillations be mitigated by injecting and/or absorbing real power at frequencies of 0.5 to 1 Hz, and may be encountered in systems with long transmission lines [23].

Voltage control support

Maintaining adequate reactive power is crucial for voltage stability. This service can be obtained by full scale converter connected to the grid without energy storage; however addition of ES is improving regulation performance.

LVRT

During the disturbance in the grid wind turbines has to keep running for certain period of the black grid. This supports grid re-establishment. Again LVRT can be done without ES but it requires additional devices and/or curtailments in power production in order to keep voltage on the DC link capacitor in safe range. Addition of ES can support LVRT by charging ES during fault and protect the DC link capacitor against overvoltage.

TABLE I
COMPARISON OF ES TECHNOLOGIES.

Technology	Power capacity [MW]	Energy Capacity [MWh]	Efficiency [%]	Lifetime	Installations (examples)	Manufacturers
PHES	30-4000	500 - 8000	70 - 85	Up to 50 years	-There is over 90 GW in more than 240 PHES facilities in the world.	Gugler GmbH, Sulzer, North Am. Hydro, Water Alchemy, Harris
CAES	50-300	500- 2500	64 - 75	Up to 40 years	-Huntorf plant, Germany, 290 MW, 580MWh - McIntosh plant, USA, 100MW, 2600MWh	Turboexpander, Alstom, Dresser-Rand, Sulzer
FES	Up to 1,6MW (for a LSF)	Up to hour (for a HSF)	80 - 90	20 years	-Usually utilized for UPS -Propulsion applications like engines and road vehicles	Active Power, Beacon, Hitec, Piller, Pentadyne, Teledyne, Urenco
SES	Up to 1MW	Up to several seconds	90 - 98	10 years	-Power quality applications - Hybrid cars	Maxwell, NESS Capacitor, EPCOS, ESMA, NEC
SMES	Up to 2MW	0,5-5MWh	90 - 99	20 years	-Several used for power quality control -In Wisconsin, a string of distributed SMES units was deployed to enhance stability of a transmission loop.	Accel, Harc, Superconductivity Inc, Intermagnetics General Corporation
Flooded LAES	0,01-10MW	Up to 40MWh	75 - 85	Up to 2000 cycles	-CHINO, California, 10MW, 40 MWh -PREPA Puerto Rico, 20MW, 14MWh	Enersys , GNB (Exide)
Valve-Regulated LAES					-HELCO Hawaii, 10MW, 15MWh -VERNON California, 3MW,4.5MWh	C&D Technologies , Hawker Energy (Enersys)
NCES	0.01–40MW	Up to several hours	60 - 70	1000 – 3500 cycles	-Golden Valley, Fairbanks, Alaska 40 MW for 7 minutes	Saft, Alcad
NaSES	Up to 200MW	Up to1200 MWh	86 - 89	4500 cycles, up to 15 years	-Rokkasho, Japan 34MW/245MWh -Hittachi Plant 8MW/58MWh	NGK Insulators
ZEBRA	-In vehicles up to several hundred kW, -Can be up to several MW	In vehicles up to several hundred of kWh -Can be up to several MWh	90	More than 3000 cycles, up to 10 years	-ZEBRA battery plant has been built in Stabio, Switzerland 40MWh -mainly in hybrid vehicles	Beta R&D
LIES	Up to several MW	Up to several MWh	90 - 95	More than 20000 cycles	-variety of portable electronic devices -there are tests in MW range	Valence Johnson Control, Lucky Goldstar Chemical, Saft, Li-Tec Battery GmbH, A123 Systems, BYD
FBES VR	Up to several MW	Up to several MWh	70 - 80	>10000 cycles, 7-15 years	-Several installations alongside with wind turbines	Prudent Energy
FBES PSB			75	>2000 cycles		
FBES ZB			75 - 80	>2000 cycles	-Two products commercially available ZESS 50kWh, ZESS 500kWh, -A few installations planned in near future with WTs	ZBB Energy

B. *Ancillary Energy Storage applications*

dP/dt limitation

dP/dt limitation of wind power output is a service that limits the rate of change of WPP. This allows to regulate additional generation fast enough to compensate wind fluctuations.

Transmission enhancement saving

In some sites (especially remote) it can happened that wind developers installed more wind power than transmission infrastructure can transfer. Addition of ES can defer grid upgrades. Energy can be stored during periods of insufficient transmission capacity and discharged when capacity becomes available [21].

Black start

The ability of a power source to go from a shutdown condition to an operating condition without assistance from the electrical grid and to then energize the grid to help other generating units start after a blackout occurs [23].

Energy arbitrage

Separation of the energy production instants and the instants of energy selling. In many grid areas the price variation can be very high from hour to hour [24]. In order to increase revenues ES system can be fully utilized, i.e., that power is purchased from the grid when off-peak wind generation is insufficient to completely charge the energy storage media [21].

Peak shaving

ES is storing energy when consumption is low and releasing it when consumption is high to flatten the typical “mountain and valley” shape of the load curve [24].

Production levelling

The production of a WTG varies with the wind. This can be leveled by ES.

Soft stop

Soft Stop ramps down the wind power plant output more slowly than the turbine ramp rate, giving other energy sources time to start up. This can e.g. be done, by the means of an ES [24].

Primary reserve

Power sources online, synchronized to the grid that can increase output immediately in response to a major generator or transmission outage and can reach full output within 10 minutes [23].

Secondary reserve

Same as primary reserve, but need not respond immediately; therefore units can be offline but still must be capable of reaching full output within the required 10 minutes [23].

Tertiary reserve

Same as secondary reserve, but with a 30-minute response time, used to restore primary and secondary reserves to their pre-contingency status [23].

Because of the fact that energy storage is expensive solution it is unlikely that single individual service may become economically viable. Thus, the effort should be put to combine as many applications as possible; however some ES applications cannot be combined with others because of different strategy of ES management.

Presented storage applications can be grouped depending on power and energy requirements of ES as it is shown in Table 2.

It can be seen that most services can be met with storage able to operate with Ps ~ 50% of nominal plant power and in time scale of 1 hour [11].

TABLE II

OVERVIEW OF ES POWER AND ENERGY REQUIREMENTS FOR GIVEN SERVICE.

	~25% of P_{nom}	**~30 -75% of P_{nom}**	**~ 100% of P_{nom}**
ms→1min	Black Start, LVRT, Voltage control, Oscillation damping	Frequency control, Reg. Reserves, Soft stop, Peak Shaving, Black Start, Oscillation damping, Inertia	Frequency control, Reg. Reserves, Soft stop, Inertia
1min – 60min	Black Start, Transmission enhancement saving, Forecast improvement	Reg. Reserves, Soft stop, Peak Shaving	Soft stop, Reg. Reserves, Peak Shaving
1-10h	Forecast improvement Energy arbitrage	Peak Shaving, Energy arbitrage, Production levelling	Reg. Reserves, Production levelling
10h→	Forecast improvement	Production levelling	Production levelling

IV. ENERGY STORAGE TECHNOLOGIES VERSUS APPLICATIONS

There are many types of ES technologies described in II but none of them is able to solve all problems of wind power integration in power system. Particular ES selection is application and timescale dependent and for WPP should be considered in relation to services that are demanded. Table 3 presents ES technologies and applications that they are able to give.

It can be seen that from the comparison of storage technologies in respect to applications, the best choices for WPP integration seems to be: PHES, CAES, LIES, FBES, NaSES and LAES. However PHES and CAES technologies placement are dependent of geological issues. Hydrogen seems to have a huge potential in a future, however present state of development of this method makes it less efficient and very expensive solution for WPP. Supercapacitors with combination with battery can be a good solution because of their very high cycling possibility. It looks like as LAES are less relevant for WPP integration than LIES, NaSES and FBES mainly because of smaller energy density, smaller depth of discharge and big sensitivity to temperature changes.

V. EXAMPLES OF ALREADY EXISTING APPLICATIONS OF ENERGY STORAGE FOR WIND POWER PLANT

Combined storage and wind turbines installations have a short history, thus there is only a few examples of the ES applications. The reason for that is the fact that ES technologies are relatively expensive solutions (at least at present). Another aspect is that until now, the electric utility grid has served as a large-scale energy balancing and redistribution system for intermittent wind energy and it provided some level of damping for fluctuating wind power. It is considered that a number of coexisting WPP and ES will

TABLE III

COMBINATION OF ES TECHNOLOGIES WITH THEIR APPLICATIONS.

Service \ Technology	Sodium sulphur	Flow battery	Lithium Ion	Supercapacitor	Lead Acid	Pumped-Hydro	CAES	SMES	Flywheel ES	Ni-Cd	Zebra
Forecast improvement	■	■	■		■	■	■			■	■
Inertia	■	■	■	■	■			■	■	■	■
Oscillation damping	■	■	■	■	■			■	■	■	■
Grid frequency support	■	■	■	■	■			■	■	■	■
Voltage control support	■	■	■	■	■			■	■	■	■
LVRT	■	■	■	■	■			■	■	■	■
Transmission enh. saving	■	■	■		■	■	■	■		■	■
Black start	■	■	■		■	■	■			■	■
Storage arbitrage						■	■				
Peak shaving						■	■				
Production levelling	■	■	■		■	■	■			■	■
Soft stop	■	■	■		■					■	■
Primary reserve	■	■	■		■					■	■
Secondary reserve	■	■	■		■	■	■				
Tertiary reserve	■	■	■		■	■	■				

increase in near future as the penetration of wind generation grows [13].

TABLE IV

COMBINED WIND POWER AND ENERGY STORAGE INSTALLATIONS

Place	Application	Specification	ES	Year
Rokkasho, Japan	Forecast improvement, Strengthening weak grid, Peak shaving shifting, Power regulation, primary reserve	34MW/245MWh for 51MW wind farm	NaS ES	2008
Tomamae Wind farm, Hokkaido	Wind turbine stabilisation	4MW/6MWh for 30.6 MW wind park	VR	2005
Ireland, Sorne Hill Wind Farm	Peak shaving, power quality and reliability improvement	1.5MW/12MWh for 38MW wind farm	VR	2006
Australia, King Island	Local residential grid strengthening, frequency and voltage control	200kW/800kWh for five wind turbines ranged 259-850kW	VR	2003
Wind power, Hokkaido	Stabilization wind turbine output	170 kW/1MWh for 270kW wind turbine	VR	2001

The list of the combined WPP and storage installments is presented in Table 4.

VI. CONCLUSIONS

Electrical energy storage is one of the most promising solutions to the challenges related to wind integration. Storage solutions require significant investments and are introducing energy losses to WPP. These features have to be weighed against the benefits that storage can provide.

There are a number of different ES technologies available on the market with different potential, characteristics and different applications that can provide to WPPs. Some of the technologies like NaSES and FBES are already having existing applications with WPP. It is also expected that LIES will play a role in the future in the WPP integration.

The main barriers for widespread commercial implementations of ES with WPPs are high cost of ES technologies, immaturity of some technologies and uncertainty over the quantified benefits. Moreover, the future shape of the electricity market will affect decisively the viability of electrical energy storage. Future scenarios in deregulated market like ancillary services trading and storage as a paid service offered to the grid can be decisive [18]. Government subsidies for ES would also speed up widespread use of the new ES installations with WPPs.

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