Application of Wind Energy in Combination with Energy Storage

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ABSTRACT

This paper provides an introduction to the application of energy storage in combination with renewable energy, particularly with wind energy. The main objective is to explain the effect of the application of some of these available technologies for accumulating energy to solve problems with different time scales that appear in the electrical market.

The first example presented in this paper is the combination of a system of energy storage in a wind farm to provide frequency regulation to the grid. In this case the energy is stored in batteries.

At present, the most efficient method of storing massive amounts of electrical energy is achieved by transforming it to potential energy by the transport of water quantities from a lower elevation water body to a higher one. The energy transformations require the use of pumps and hydraulic turbines to complete the cycle. This method of energy storage is known as the hydro pumped storage and can be used to move peaks of electrical production and consumption for characteristic times of the order of hours or greater. The combination of this technology with wind generation could be a clear solution to reduce the dependence of some territories of external energy sources. In the case that this territory has a high level of hydroelectric infrastructure the application of this technology would be more attractive as the most expensive part of the equipment is already installed.

Keywords: *Renewable energy, energy storage, grid regulation.*

INTRODUCTION

The electrical grid of most countries such as Brazil is a vast network that transmit power from generation sources to the demand points. The operator of the grid has to ensure that the balance between electricity supply and demand is maintained during the grid operation. Any disturbance in this balance would modify the characteristics of the supply of energy. The voltage, frequency or phase of the grid should be maintained inside of a prescribed interval to avoid any damage to the end users or possible blackouts.

When an imbalance occur, the frequency that the users of electricity expect (60 Hz or 50Hz depending on the continent) is not maintained. If generation exceeds consumption, the frequency increases, and when generation is less than the aggregate load, the frequency decreases.

The systems and control mechanisms used to maintain the characteristics of the Power System have to manage different time scales are normally called ancillary services, e.g. voltage control, frequency support, power (spinning) reserve, power dispatch and others. Traditionally these ancillary services are supplied by conventional power plants equipped with synchronous generators.

The need for ancillary services in power systems increases as renewable power penetration grows [1], since these technologies introduce balancing issues (among others) due to their natural variability. Additionally, some of these technologies do not behave as synchronous machines.

It is known that generation plants using wind turbines with partial or full power electronic conversion can regulate their active and reactive power output to provide voltage and frequency support, and these are commonly used. Recently, interest has grown in the feasibility to provide so-called Inertial Response and Power Oscillation Damping [2].

However, any temporary increase in active power (‘overload’) is limited by the structural strength of the turbine design, unless the turbine is operated below its available power ('curtailed') prior to the increase in active power. To harvest as much wind energy as possible, operation without curtailment of active power output is preferred and almost exclusively used.

There are recent publications indicating a short-term overload (some per-cent for a few seconds [3]) may be offered by particular turbines when operating in the partial or full load range (i.e. at medium winds or when the available wind power exceeds turbine nameplate rating). Nevertheless, this action causes a power dip after turbine's temporary contribution if power output goes beyond the available from wind [4]. But as a generally valid concept, across all operating conditions, wind power plants can easily offer reduction of active power, while any increase of it requires previous curtailment.

The application of an Energy Storage System (ESS) with a very short characteristic time in combination with the wind farm offers an output that could be qualify as ancillary service without the need of reduce the production of the wind turbine (curtailment) or increase the output of the turbine beyond its nominal value (overload).

The previous example of combination of energy storage with wind farm has a short response time to adapt to the requirements of an ancillary system. When the energy storage system has a longer characteristic time the capability of balancing the production and consumption can be extended to days, seasons or even years [5]. In that case the response time of the system is longer and a higher amount of energy is involved.

The paper is organized as follows. In the first part of the paper the results of an experimental wind farm contributing to the frequency regulation are presented. The second part of the paper introduces the analysis of possible use of a combined wind farm with hydro pump storage for El Hierro Island. Last section presents the conclusion of this paper.

ENERGY STORAGE SYSTEMS FOR FREQUENCY REGULATION

A 1.6MW/0.4MWh battery energy storage system was installed in Western Denmark and operated for provision of frequency regulation. This was the first unit of this type installed in the Danish or even Nordic transmission network.

It was originally installed for purposes of research into the properties of integrating energy storage into a wind power plant, and now the facility operates autonomously. The transmission system operator (TSO) in Western Denmark is Energinet.dk, who daily auctions approximately ±25MW frequency-controlled primary reserve capacity [6]. The primary reserve product, was defined for this particular case as: “Regulation must be supplied at a frequency deviation of up to +/- 200 mHz relative to the reference frequency of 50 Hz. This will normally mean in the 49.8-50.2 Hz range. A deadband of +/- 20 mHz is permitted. The reserve must as a minimum be supplied linearly and be fully activated within 30 seconds in the event of a frequency deviation of +/- 200 mHz.”. Figure 1 shows the regulation bands.

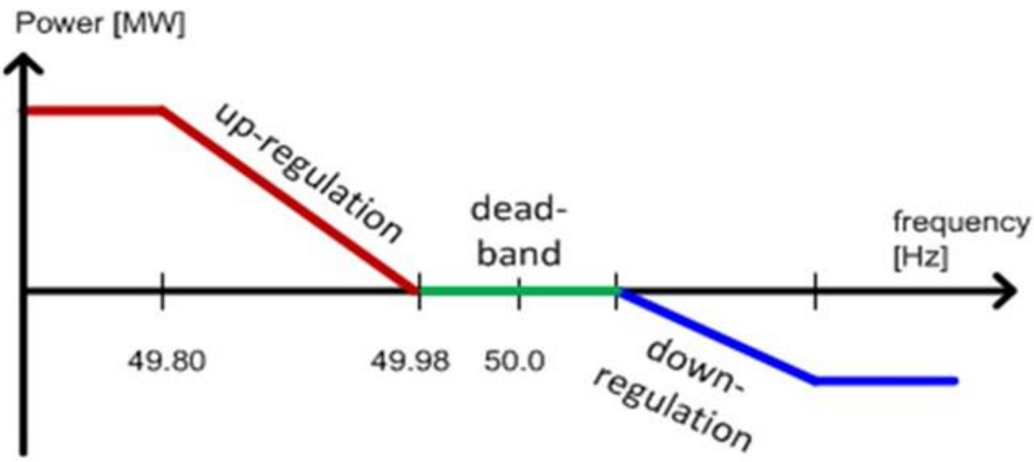

Figure 1 – Primary reserve profile of power vs frequency.

The energy storage is composed of two different systems, from separate suppliers of different types of Li-ion batteries, are combined in the installation which is located in a 150kV substation. They each connect to a 10kV bus and via 60/10kV and 150/60kV transformers to the sub-transmission network. Auxiliary power is supplied via a separate 10/0.4kV transformer to both energy storage systems (ESS), see Figure 2.

The power electronic DC/AC converters operate in all four quadrants (P+jQ) on their 480V AC side. The battery management systems govern state of charge, temperatures and limits charging/discharging currents to safe levels.

All electrical measurements take place at 10kV level and feed back to a master-level controller, which dictates setpoints for active and reactive powers, and receives information about state of charge for use by its control laws. Frequency calculations are updated every 10ms, while power references are updated every 100ms.

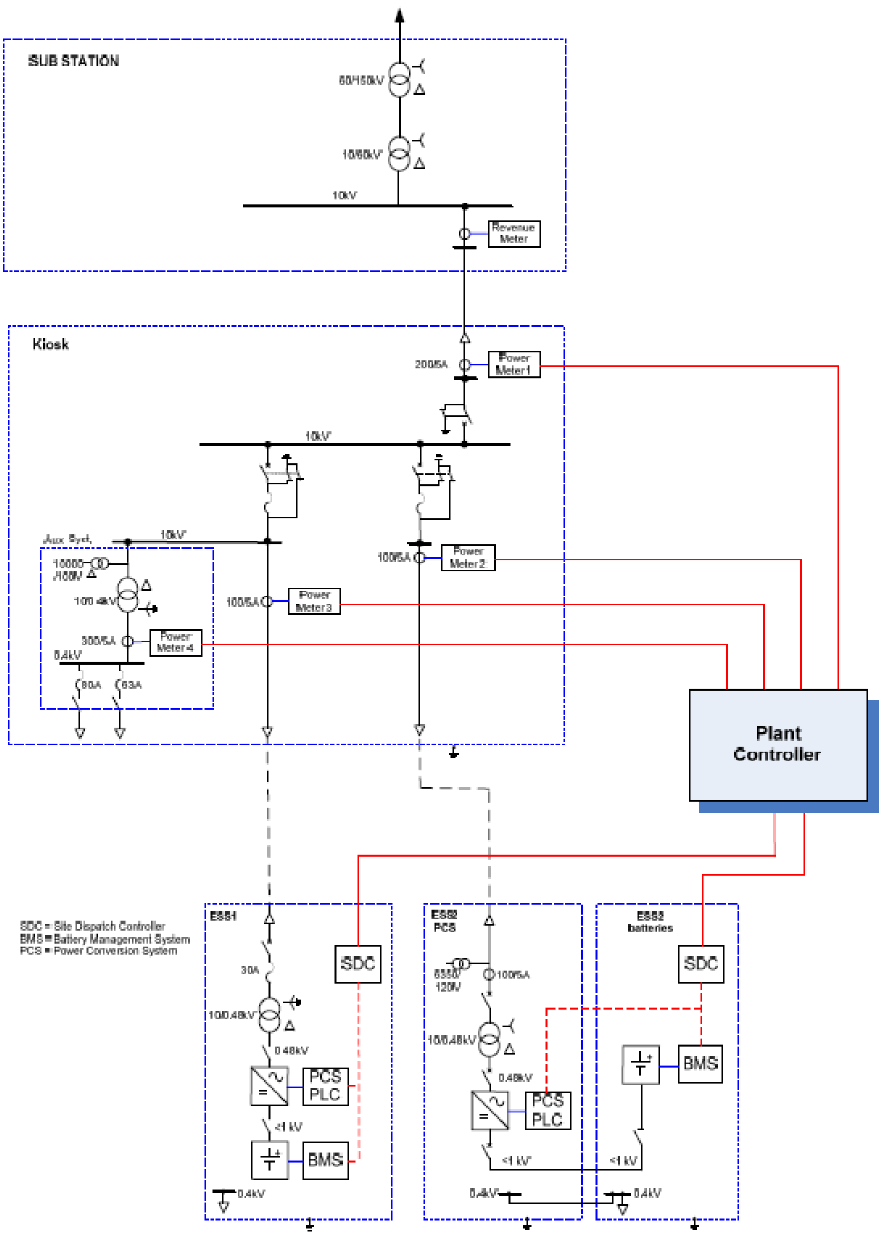

Figure 2 – Single line diagram of energy storage system including measurement points

This ESS has been qualified by Danish transmission system operator Energinet.dk to deliver primary reserve, ie. frequency regulation. The technical requirements can be found in [6]. Outside the deadband of ±20mHz, active power must increase linearly with the frequency deviation until ±200mHz is reached. Three distinct tests were conducted: (i) linearity; (ii) 15-minute duration; and (iii) response time. Results of these test can be seen in Figure 3.

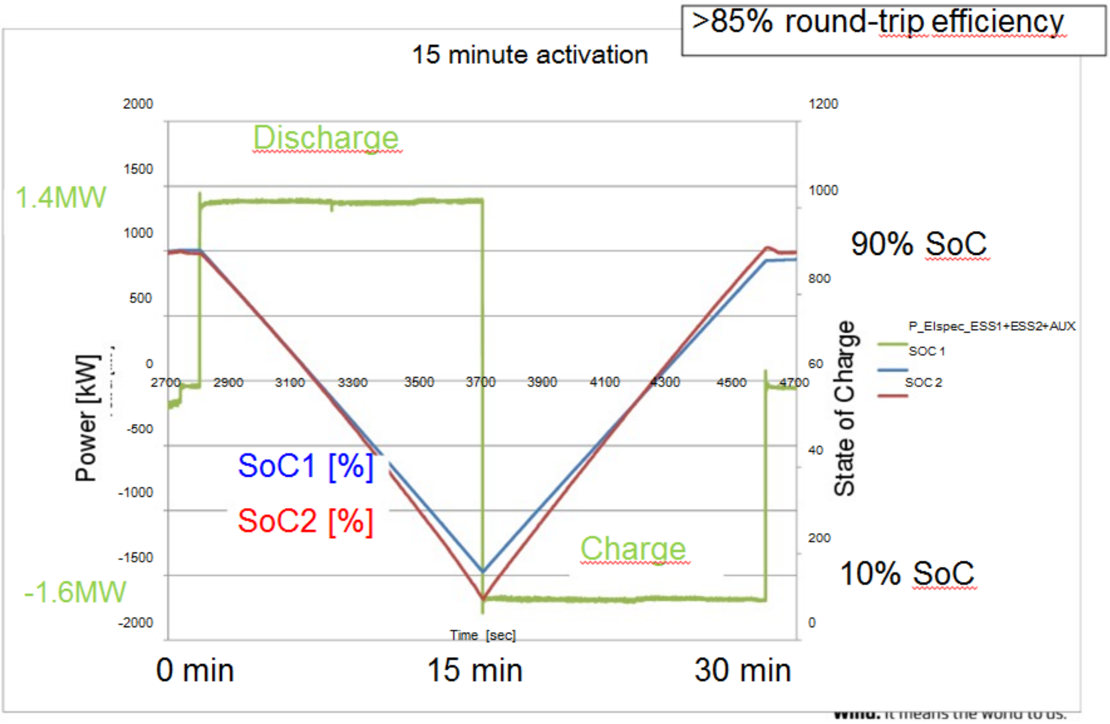

Figure 3 – Recording of power and SOC vs time from qualification tests

Figure 4 shows the results obtained during the operation of the system for frequency regulation. The system has also the capability of damping oscillations in the power system (PSO).

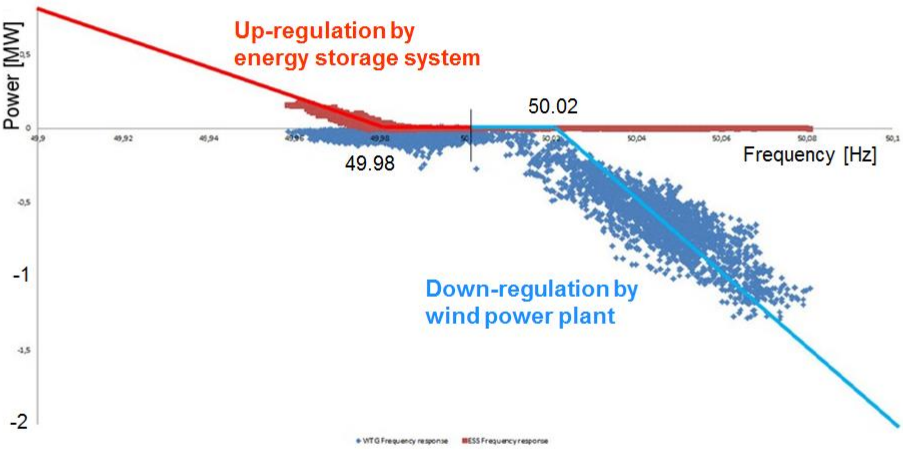

Figure 4 – Operation of power plant during frequency regulation

MASSIVE ENERGY STORAGE

When massive energy storage is considered the only realistic alternative is the use of hydro pumped storage or compressed air. The other current possibilities do not offer a mature product with enough level of maturity and with sufficient effectiveness. In Table 1 a comparison of different possibilities to accumulate energy are presented. Please note that prices could have changed with respect to the ones in the table because new improvements are applied mainly in the accumulation technology.

The application of air compressed for accumulating energy requires the use of conventional fuel to increase the temperature of air before extracting energy in the turbine. The main advantage of this technology is that compression work has been done by wind turbine previously. Heat from exhaust gases can be used to increase the temperature of compressed air before entering the combustion chamber. As compression work was done previously and exhaust heat is recovered almost all the chemical energy in the fuel can be transformed to mechanical energy. However about half of the energy used to compress air is lost because air has to be stored at high pressure to minimize the volume of reservoir and it is used several hours or days before the compression. The temperature of air is much higher than the ambient one after the compression, this temperature will be gradually decrease up to reach an equilibrium with the external one except some isolation is provided. Even with a high level of isolation air temperature will decrease to external one for a sufficient long time.

Table 1 Technical characteristics of main storage technologies

Technology	Investment costs	Energy density	Efficiency	Maturity	Maximum Existing Capacity
Pumped Storage	~ 100 €/kWh ~ 1000 €/kW	1 kWh/m^3 (400 m)	70 %<η<80 %	Fully Mature	Power ~ 2000 MW Energy ~ 1 TWh
Redox Flow Accumulators	~ 200 €/kWh ~ 1500 €/kW	50 kWh/m^3	η~75 %	Mature	Power ~ 10 MW Energy ~ 10 MWh
Electrochemical Accumulators	~ 500 €/kWh ~ 2000 €/kW	50-200 kWh/m^3	60 %<η<80 %	Mature	Power ~ 25 MW Energy ~ 50 MWh
Hydrogen Fuell Cells	~ 50 €/kWh ~ 6000 €/kW	500 kWh/m^3 (at 200 bars)	30 %<η<50 %	Pilot phase	Small scale
CAES (50 bars)	~ 50 €/kWh ~ 500 €/kW	5 kWh/m^3 (at 50 bars)	η<50 %	Almost mature	Power ~ 300 MW Energy > 600 MWh

There are some projects in operation that combine wind energy with pumped storage. In particular there is a wind farm coupled with wind turbines in the El Hierro island, one of the Canary Island in Spain. Currently the whole electrical need of the island is covered with wind energy and uses the hydro pumped storage to balance demand and production.

The wind conditions and characteristics of this island have been used to perform an analysis of the performance of the system in terms of cost of energy. Due to the size and population of this island the maximum generation to cover the demand is lower than 10 MW what makes it very attractive for a pilot test.

The first step in the analysis is determine the curve of demand and the possible production of wind turbines. These value have been determined for the twelve months and in intervals of 1 hour. To simplify the analysis it has been assumed that the production and consumption is constant for a particular hour during the whole month. The value of monthly consumption (MWh) has been obtained from grid operator in Spain (Table 2).

Table 2 Results obtained for El Hierro

Month	Consumption	Prod	Units
January	3100	745	5
February	2800	722	4
March	3200	800	5
April	3100	696	5
May	3400	653	6
June	3500	400	9
July	3900	532	8
August	3800	470	9
September	3500	564	7
October	3500	714	5
November	3200	773	5
December	3200	867	4

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Once the data for consumption and wind production is available for all hours in the different months of the year are known it is possible to determine the minimum number of wind turbines needed to cover the demand. The values of unitary production of a V100-2.0 MW wind turbine per month in MWh and the number of units required to cover the monthly production is also included in Table 2.

The minimum number of wind turbines to cover the monthly consumption is four in Winter due to the reduction of demand and the relative high wind of this season. During summer the combination of low wind with higher consumption makes necessary at least nine wind turbines to balance the energy demand.

The annual cycle is analysed assuming that during the months with exceedance of wind energy water is pumped to cover the deficit during summer. It has been supposed the existence of a conventional generator that cover part of the demand. The amount of energy to be stored to cover the annual cycle is presented in Figure 5 as a function of number of wind turbines.

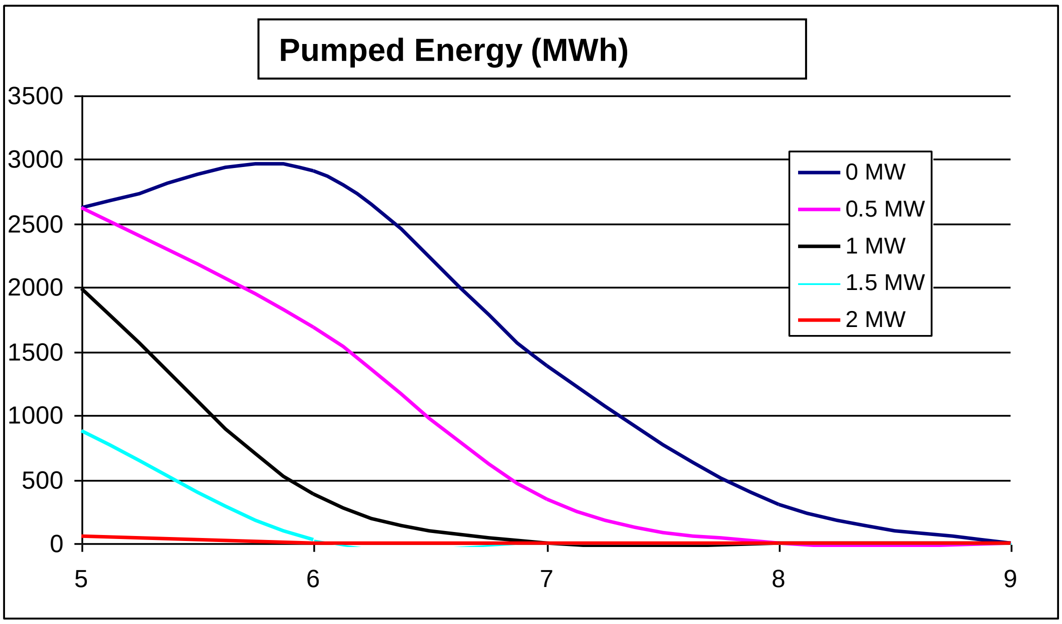

Figure 5 – Energy stored to cover annual demand

The cost of energy is dramatically decreased when wind energy is included in the energetic mix. Due to the size of the island the conventional generator are just diesel engines with relatively low performance when compared with other methods of producing electricity. In this particular case the price of energy is of the order of 120 €/MWh when no wind energy is used. The price of energy reaches a minimum of 30 €/Mwh for eight wind turbines and a thermal supply of 0.5 MW.

CONCLUSSIONS

The combination of Energy storage with Renewable Energy generation can be applied to achieve different objectives depending on the time scale of the storage. For short response time the storage can be deployed for frequency regulations purposes and a successful case for this application has been presented based on a 1.6MW/0.4MWh system in Westen Denmark. This system has been successfully tested to provide primary reserve response requested by grid operator Energinet.dk at that region.

For long term storage different technologies have been presented from which a business case was detailed on combined wind and pumped storage for the island El Hierro, in Spain. All the demand of that island is supplied by this renewable energy solution and an economic analysis has shown that the cost of energy of such solution is considerably lower than the estimated cost of an alternative conventional diesel generator solution.

With the increasing penetration of Wind Energy in the Brazilian Energy Matrix at regions far from consumption center the frequency response solution presented in this paper can be explored as one option to provide primary regulation required for safe operation of the system in those areas. Furthermore, if one considers the characteristic of Brazilian generation system being hydro based and the complementarity of the wind and rain regimes in the country, the wind pumped energy storage solution discussed in this paper can be explored as an alternative to cope with intermittency of both sources and to increase even further the possible penetration of these renewable energy generation sources in the Brazilian energy matrix.

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BIOGRAPHIES

Rafael De Vecchi – was born in Ourinhos, São Paulo-Brazil on May 9th 1984. He has graduated in Electrical Engineering in 2008 from the Technological Federal University of Paraná in Curitiba, Brazil and holds a M.Sc. Degree in Renewable Energy from the University of Oldenburg, Germany, 2011.

He has been heavily involved in the Wind Industry and participated in several international Renewable Energy Conferences. From 2010 until 2012 he worked in Wind Industry in Germany and since then he is working on the Wind Industry in Brazil. Currently he is responsible for Technical Bid Management in Vestas Brazil.

Alvaro Matesanz Gil – was born in Spain. He has a M.Sc. in Aeronautical Engineering in 1987 from the Universidad Politecnica de Madrid and he is Doctor on Mechanical Engineering from the Universidad Carlos III de Madrid since 1998.

He has been heavily involved in the Wind Industry and participated in several international Renewable Energy Conferences. From 2003 until 2008 he worked in Gamesa and since 2008 he is working in Vestas