ADDITION OF ENERGY STORAGE TO WIND POWER GENERATION

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Abstract **– The continuous growth of the wind power generation presents problems to the operation of power systems. Due to the development of energy storage systems (ESS) with better performance, it is possible to use the energy storage as a reserve to regulate variations of power generation and demand. Those aspects are analyzed in the present paper. The principal characteristics of the ESS are also studied.**

Keywords **– wind power generation, power systems, energy storage systems, generation reserve**

I. INTRODUCTION

The growth of the dispersed generation installations is due to the continuous search for primary energy sources that can contribute with the electric supply without damaging the environment. This leads to a better exploitation of renewable energetic resources such as those ones provided by the sun and the wind. These energy types present the problem of availability of the primary resource that suffers important variations, which can be of a foreseeable kind (day/night cycle) or not (weather conditions). To cover the shortage of generation power caused by these variations, it is necessary to provide a sufficient amount of generation reserve. Thus, if the wind power generation goes on growing, it will become excessively onerous for the system to keep the stated reserve.

Owing to the development of energy storage systems (ESS) with better performance and lower capital costs, it is possible to use the energy storage as a reserve to regulate variations of power and demand.

II. CHARACTERISTICS OF ENERGY STORAGE SYSTEMS (ESS)

Table I summarizes the main characteristics of the storage systems. In what follows the different ESS are briefly described.

TABLE I
Characteristics of the energy storage systems

Nomination	Power range	Discharging times	Response times
Pumped hydro storage	100 - 2000 MW	4 – 10 h	< 15 s
CAES	10 – 300 MW	1 – 20h	9 – 12 min
Flywheels	5 kW – 1.5 MW	15 s – 15 min	< ¼ cycle
SMES	10 kW – 1 MW	5 s – 5 min	< ¼ cycle
Supercapacitors	kW – 100 kW	s – 1 min	< ¼ cycle
Batteries	kW – 50 MW	1 min – 3 h	< ¼ cycle
Fuel cells and VRB	kW – 2 MW	min – h	< ¼ cycle

A. Pumped Hydro Storage

The pumped hydro storage consists of two big reservoirs of water placed at different heights, generally built by dams. In the unloading process, the water in the upper reservoir is turbined and placed in the lower reservoir. Turbines move generators that produce the necessary electric energy. In order to storage energy, the water in the lower reservoir is pumped and placed in the upper reservoir, ready to be used when necessary.

Depending on the size of dams, they are capable of delivering up to 2 GW during 10 hours. The performance is of eighty per cent, being able to store their energy for more than half a year. Thanks to the development of advanced pumped systems (APS), it is possible to change from “pump” to “turbine” mode in less than 15 seconds [1]. Due to their ability to store big amounts of energy and their simplicity of design, the capital cost per unit of energy is the cheapest [2]. Besides, it does not produce pollution or waste.

On the other hand, these systems depend on specific geological formations for their installation. It is necessary that there are two big water reservoirs separated by a considerable vertical distance, but not very far horizontally [3]. For this reason these plants are located at remote places, such as mountains, where the construction is difficult and the electric network is far away.

B. Compressed Air Energy Storage (CAES)

In the process of loading, electric energy is absorbed from the network to activate a compressor that pumps pressurized air to an underground cavern. The air is previously cooled to make the best use of the available storage capacity. In order to perform the “unloading”, the pressurized air is preheated, mixed with small amounts of gas, and burnt in the turbine that drives the generator in charge of the production of electric energy.

It can provide up to 300 MW during 20 hours, depending on the plant size with a performance of about 85 %, the energy can be stored for more than a year. The response times vary between 9 minutes for an emergency start, and 12 minutes for an ordinary start. Besides, if natural geological formations are used, the CAES system installation does not require a high investment [1].

However, the CAES system is profitable only if there are caverns with a solid, reliable structure for this purpose. There are not many caverns of this kind in the world, a fact that limits the use of this storage method [1].

C. Flywheels

Basically, a flywheel is a spinning disc (rotor) with an axis used for rotation. Its axis is connected to an electric machine.

Generally, an AC/DC converter implemented with power electronics is the interface to transmit power between the electric system and the flywheel (Figure 1). The energy is transferred to the flywheel when the electric machine operates as an engine, accelerating the flywheel. The flywheel is discharged when the electric machine regenerates through the drive, slowing the flywheel. The stored energy depends on the inertia moment I of the rotor and the square of flywheel velocity w (1). The inertia moment of the rotor depends on its radius r, mass m and rotor length h (2) [4].

$$Ekinetic=\frac{1}{2}Iw^2 \tag{1}$$

$$I=\frac{r^2mh}{2} \tag{2}$$

The storage capacity can be improved increasing the inertia moment (low-speed flywheels), or the operation velocities (high-speed flywheels), or a combination of both alternatives [4]. In general, materials with a greater density present a smaller mechanic specific resistance. As a consequence, they can support smaller efforts; thus, operating at lower speed.

The modern flywheels are modular, with power ranges varying from kilowatts to megawatts, and they can be grouped to form a storage system with the required power and energy. The response time is lower than a quarter of a cycle, and its performance is of 90 %. However, with an energy loss of 1 % per hour due to friction [1], they are not efficient to store energy for long periods. Besides, it is the alternative with highest capital cost, being profitable only for storage in a small scale [2].

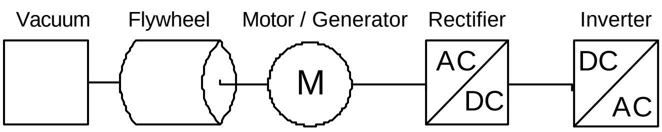

Fig. 1. Traditional flywheel with rectifier.

D. Superconducting Magnetic Energy Storage (SMES)

An SMES unit is a device that stores energy in a magnetic field generated by the direct current flowing through a superconducting coil. Once the magnetic field is established in the coil, the direct current will circulate indefinitely, because the superconductor material offers no resistance to the passage of dc current. The stored energy (3) and its power (4) can be expressed as:

$$E=\frac{1}{2}LI^2 \tag{3}$$

$$P=\frac{dE}{dt}=LI\frac{dI}{dt}=VI \tag{4}$$

Where L is the inductance of the coil, I is the dc current flowing through the coil, and V is the voltage across the coil. Since energy is stored as circulating current, energy can be drawn from an SMES unit with almost instantaneous response, with energy stored or delivered over periods ranging from a fraction of a second to several minutes.

An SMES unit consists of a large superconducting coil at the cryogenic temperature. This temperature is maintained by a cryostat contained in helium or nitrogen liquid vessels. A power conversion/conditioning system (PCS) connects the SMES unit to an ac power system, and it is used to charge/discharge the coil (Figure 2).

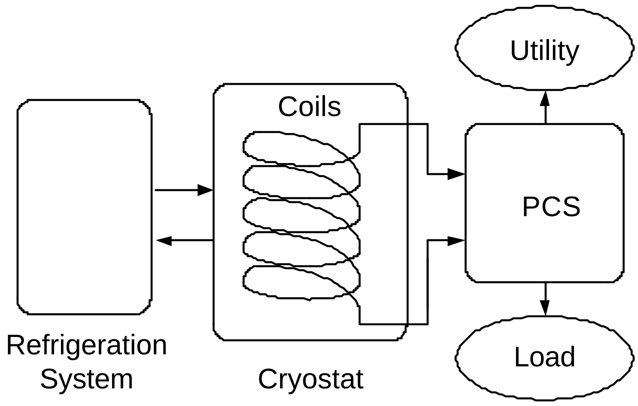

Fig. 2. Superconducting magnetic energy storage system (SMES).

An SMES unit can repeat the charging and discharging sequence indefinitely without worn-out its components with a response time lower than a quarter of cycle. Nowadays, they are capable of supplying up to 10 MW in less than 10 seconds; but, it is expected that this technology can supply up to 2 GW [1]. In addition, these devices do not produce substances aggressive to the environment. Thanks to the development of high temperature-superconductors, it has been possible to reduce the capital costs per unit of stored energy, becoming one of the cheapest storage methods [2].

E. Supercapacitors

Capacitors consist of two conductive parallel plates separated by a dielectric insulator (Figure 3). Plates hold opposite charges which generate an electric field. Unlike batteries where energy is stored in chemical form, capacitors store energy in the electric field. The capacitance, C, represents the relationship between the stored charge, q, and the voltage between plates, V, as shown in (5). The capacitance depends on the permittivity of the dielectric, e, the area of plates, A, and the distance between plates, d, as shown in (6). Equation (7) shows that the energy stored on the capacitor depends on the capacitance and on the square of the voltage.

$$q=CV \tag{5}$$

$$C=\frac{eA}{d} \tag{6}$$

$$E=\frac{1}{2}CV^2 \tag{7}$$

The amount of energy that a capacitor is capable of storing can be increased by either increasing the capacitance or the voltage applied on the capacitor. The applied voltage is limited by the dielectric strength (which impacts the distance between plates). Capacitance can be increased by increasing the area A of plates, increasing the permittivity e, or decreasing the distance d between plates.

Thus, supercapacitors are double layer capacitors that increase energy storage capability due to a large increase in the surface area through the use of a porous electrolyte (they still have relatively low permittivity and high dielectric strength). Several different combinations of electrode and electrolyte materials have been used in supercapacitors, with different combinations resulting in varying capacitance, energy density, life cycle, and cost characteristics. At present, supercapacitors are most applicable for high peak-power, low-energy situations. A supercapacitor can provide extended power availability during voltage sags and momentary interruptions. Supercapacitors can be kept completely discharged, easily installed, they are compact in size, and can operate effectively in diverse (hot, cold, and moist) environments. Supercapacitors are now commercially available at lower power levels.

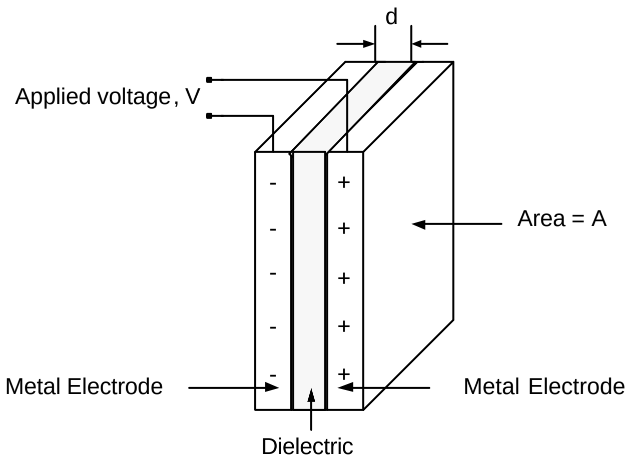

Fig. 3. The principle of capacitors.

Since the process of conversion of energy is direct, the supercapacitors have a response time lower than a quarter of a cycle. In addition, losses by Joule effect are negligible thanks to their low internal resistance, resulting in a performance of about 95 %. The process of charging and discharging can be repeated an unlimited number of times without resulting in degradation, making their life longer. They do not produce substances aggressive to the environment either. However, these devices store up to 0.5 kWh, so they are not good to provide energy during long periods of time (minutes-hours).

F. Batteries

A battery system is made up of a set of low-voltage/power battery modules connected in parallel and series to achieve a desired electrical characteristic. Batteries are “charged” when they undergo an internal chemical reaction through a voltage applied at their terminal nodes. They “discharge” when they reverse the chemical reaction. Key factors of batteries for storage applications include: high energy density, high energy capability, constant efficiency, cycling capability, life span, and low capital cost. Batteries store dc charge, so power conversion is required to connect a battery with an ac system. Small, modular batteries with power electronic converters can provide four-quadrant operation (bidirectional current flow and bidirectional voltage polarity) with fast response [4].

Batteries have a modular design and they are easy to transport, it is possible to configure an arrangement of batteries to adapt to the desired power and energy requirements, with response times of about milliseconds. However, due to the chemical nature of the storage process, they can not provide high power during long periods of time. Moreover, the charging and discharging cycles degrade the materials reducing their useful life. It is important to mention that chemical reactions produce toxic gases that pollute the environment.

G. Fuel Cells

Fuel cells (FC), the same as batteries, turn the energy chemically stored into electric energy. A Fuel Cell converts the chemical energy of a fuel, just as the Hydrogen (H_2), and an oxidizer, just as the oxygen (O_2), in electrical energy. A fuel cell consists of two electrodes, known as anode and cathode that are separated by an electrolyte (Figure 4). Oxygen is passed over the cathode and hydrogen over the anode. Hydrogen ions are formed together with electrons at the anode. Hydrogen ions migrate to the cathode through the electrolyte and electrons produced at the anode flow through an external circuit to the cathode. At the anode they combine with oxygen to form water. The flow of electrons through the external circuit provides the current cell [1]. In order to storage energy, Hydrogen and Oxygen are obtained from water by passing a direct current in a process known as electrolysis.

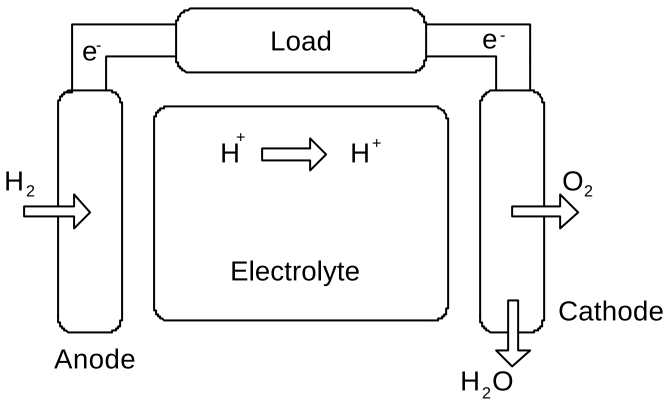

Fig. 4. General scheme of a fuel cell.

Under ordinary operation conditions, a fuel cell produces between 0.5 and 0.9 V at its terminal nodes [5]. In order to be used in power systems, it is necessary to have an arrangement of cells connected in series and parallel to adjust to the desired voltage and current requirements.

Different types of fuel cells have been developed using the same operation principle, each one with advantages and disadvantages respect to the others. The alkaline FC (AFC) achieves a performance of 60 % operating at temperatures between 90 and 100 ºC, and it can supply 100 kW. The FC with polymer membrane (PEM) works at 80 ºC and produces 250 kW. Meanwhile, a performance of 85 % operating at 650 ºC, and a 2 MW supply can be obtained using FC of fused carbon (MCFC) [1]. In general, the response time of an FC is about fractions of cycle and allows storing up to 2 MWh. Integrated with FACTS devices, the FC is suitable for applications of very short duration (fractions of cycle), short duration (seconds-minutes) and long duration (minutes-hours). In addition, the combustion only produces water, which is not aggressive to the environment. However, if the FC is integrated with dispersed generation like wind generation, the intermittent operation of the FC (charge/discharge) may cause impurity of hydrogen and oxygen and vice versa; with a high risk of explosion [6].

H. Vanadium Redox-flow Battery (VRB)

The VRB is an electrical energy storage system that converts chemical energy into electrical energy and vice versa. Energy is stored chemically in different ionic forms of vanadium in a dilute sulphuric acid electrolyte. The electrolyte is pumped from separate plastic storage tanks into flow cells across a proton exchange membrane (PEM) where one form of electrolyte is electrochemically oxidized and the other is electrochemically reduced (Redox: Reduction-Oxidation). This creates a current that is collected by electrodes and made available to an external circuit. The reaction is reversible, allowing the battery to be charged, discharged and recharged [7].

The principle of the VRB-ESS is shown in more detail in Figure 5. It consists of two electrolyte tanks, containing active vanadium species oxidation states (positive: V(IV)/V(V) redox couple, negative: V(II)/V(III) redox couple). These energy-bearing liquids are circulated through the cell stack by pumps. The stack consists of many cells, each of which contains two half-cells that are separated by the PEM. In the half-cells the electrochemical reactions take place on inert carbon felt polymer composite electrodes from which current may be used to charge or discharge the battery.

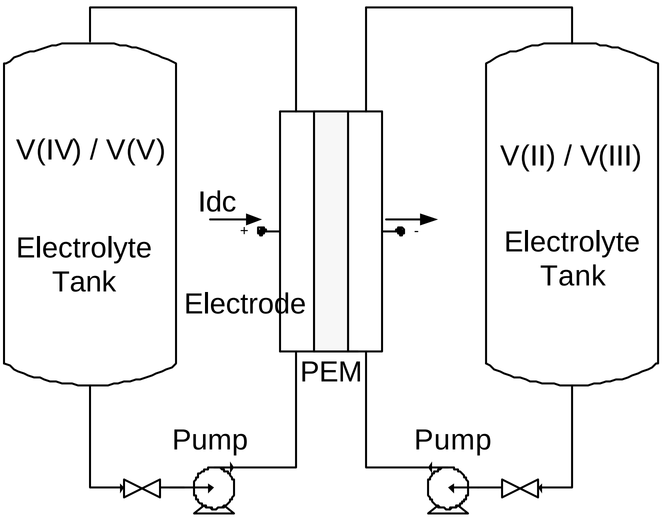

Fig. 5. General scheme of a VRB.

Equations 8 and 9 show the electrochemical reactions, the left-to-right reaction occurs during charging and the right-to-left reaction occurs during discharging.

Positive electrode: $V(IV) \Leftrightarrow V(V) + e^-$ (8)

Negative electrode: $V(III) \Leftrightarrow V(II) + e^-$ (9)

The battery produces a nominal cell potential of approximately 1.25 V, depending on the concentration of the vanadium. As with other flow batteries, useful terminal voltages are achieved by series connection of many cells into a "stack". The amount of power available is related to the stack voltage and the current density established through the cell, while the energy available depends only on the supply of charged electrolyte to the stack. So, the rated power and the energy stored can be readily upgraded by increasing or decreasing the stack and the electrolyte tank respectively.

The VRB has a quick response time and an outstanding high-rate output performance over short time periods. As an example, a VRB has demonstrated a response time of 350 µs, and at a state of charge (SOC) of 90 %, displayed the high-rate output performance of 4.5 times the rated output for one second and three times the rated output for one minute. The VRB can achieve high energy efficiencies (80 – 85 %), including the pumping energy losses. Another positive feature of VRB is their long life time, up to 13,000 cycles of charge/discharge. There is no emission of CO2 and the electrolyte is recyclable, making the VRB environmentally friendly [8]. By utilizing all these features, the VRB can be an effective system not only for conventional load leveling applications but also for momentary voltage sag compensation and stabilizing the output fluctuations of the wind generation.

III. SECURITY REQUIREMENTS OF POWER SYSTEMS

Dispersed generation is an electric power source directly connected to the distribution network or at the consumption point [9]. Technologies generally used are: turbo-gas units, steam turbines, hydraulic turbines, solar panels, wind generation, among others. Typical power ranges vary between Kilowatts and tens of Megawatts.

Generally, generators are connected to the transmission system. In case of dispersed generation, the connection of a generator to the distribution network produces a big impact on the operation and control of the whole system. It is necessary to consider different technical and operational aspects [10]:

- Distribution networks generally have a radial or ring loop design, and a not meshed transmission network. Then, the power flow is not unidirectional and the fault current can change its magnitude, direction and duration; and therefore, protections selectivity must be checked.
- Transmission lines present a high X/R characteristic, which causes a voltage fall along the line lower than in the case of a distribution line, where resistance and impedance parameters are similar. For this reason, the connection of the disperse generator influences on the local voltage level.
- Instead of synchronous machines, the disperse generators generally use asynchronous or induction machines. Although the second ones are cheaper, they are not capable of providing reactive power and absorb reactive energy during the start and the ordinary operation. Thus, manufacturers provide capacitors banks and converters with power electronics.

- When the penetration level of disperse generation is bigger, the complexity of the Control System and the Data Acquisition (SCADA) increases.
- In case of fault, it would be important to maintain isolated areas stable after the event has been overcome. In this context, the disperse generator must be installed with control devices that allow regulating the frequency and voltage through the injection of active and reactive power, respectively.
- The higher the penetration of dispersed generation, the greater the reserve capacity of generation needed in the system. This reserve can be supplied by conventional generators operating under their maximum capacity (rotating reserve), or through the use of energy storage. In case of using the rotating reserve, such generators operate in a less efficient way, which results very onerous for the system. As a result, the use of a storage system as generation reserve must be considered.
- To solve the problem of the short-term and long-term variations of the wind power generation, it would be important to incorporate ESS in order to control the system frequency during the first cycles (Primary Frequency Control) and over periods ranging from second to several minutes (Secondary Frequency Control).

IV. SELECTION CRITERIA

The selection of a specific energy storage technology for a certain application implies to establish previously a set of selection criteria which allow making an appropriate decision. The main characteristics of the ESS have different priorities, depending on their application. The most important criteria to be considered are:

- Application Type.
- Modular Design.
- Sitting Requirements.
- Specific Energy.
- Efficiency.
- Lifetime.
- Charging Time.
- Charge / Discharge Ratio.
- Capital Cost.
- Maintenance Cost.

In the case of incorporate ESS with wind generation, it is important to have low sitting requirements and modular design. Because of this, the pumped hydro storage system and compressed air energy storage system do not meet this requirement.

Supercapacitors are remarkable for its exceptional response, very low maintenance requirements and high robustness. Flywheels, on the other hand, stand out for their high energy density and minimum environmental impact. SMES systems stand out for their excellent dynamic performance, competitive costs and very good portability [11]. However, for the purpose of working on the secondary frequency control, they are not capable of storing and delivering large amounts of energy.

For the selection of an energy storage technology with the objective of working on the primary and secondary frequency control it is needed high frequency of charge/discharge and high discharge time (minutes – hours) respectively. Only VRB and Batteries fulfill this requirement (see Table I) and they are commercially available. The comparisons between them are listed on table II [11].

TABLE II
ESS for Secondary Frequency Control

Characteristics			
System Attribute	**Lead Acid Battery**	**Sodium-Sulfur Battery**	**VRB**
Specific Energy	18 kWh/m3	**250** kWh/m3	30 kWh/m3
Efficiency	**92 %**	88 %	85 %
Lifetime	400 cycles	1000 cycles	**13000 cycles**
Charging Time	3 hours	3 hours	**10 min**
Charge / Discharge Ratio	5/1	5/1	**1**
Capital Cost	**125** $ / kWh	350 $ / kWh	600 $ / kWh
Maintenance Cost	0.02 $ / kWh	0.02 $ / kWh	**0.001** $ / kWh

Although the capital cost of the VRB system is the most expensive, this option represents the cheapest alternative thanks to their lifetime, up to 13,000 cycles. The VRB has a Charge/Discharge Ratio equal to 1, and nowadays is commercially available.

By considering the frequency control mode, the cost of systems and the required performance imposed, the Vanadium Redox Flow Battery Systems are currently most adequate for the present application.

V. CONCLUSIONS

Nowadays, the wind generation is the technology of renewable energy with the greatest growth in the last years. In 2002, the installed wind turbines increased a 32% in the world. In case of Argentina, the installed power is 12 MW, and the potential of production is about 500.000 MW [12]. Although a deep analysis on wind energy generation exceeds this paper, in a future work a wind energy generator integrated with a VRB for primary and secondary frequency control mode will be analyzed.

Such choice is based on the fact that the VRB has the following characteristics: modular design, low installation cost, low operation and maintenance costs for the selected power scale [2], it adjusts to requirements of power of an ordinary wind generator (up to 750 kW) [12], load leveling capacity, exceptional response, high energy density for secondary frequency control purposes and low environmental impact.

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