EVALUATION OF ENERGY STORAGE SYSTEMS FOR APPLICATION IN THE FREQUENCY CONTROL

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***Abstract* - In the power systems the operation security is given by the maintenance of enough "short-term generation reserve". After eventual faults of generating units, reserve should be appropriately activated -as much in quantity as in speed- through the frequency control to maintain the system frequency above the acceptable minimum. Nowadays the energy storage systems are a real alternative to decrease the reserve power of the generators. Through the use of adequate storage devices, it is possible to store exceeding energy for its application in the frequency control in substitution of the generators power reserve. Using these storage devices, jointly with new power electronics devices to control the energy input-output, could be also carried out a more efficient frequency control. In this article, the main current energy storage systems are evaluated for application in the frequency control of the electric systems. Based on defined criteria, the most adequate devices for the mentioned application are determined.**

I. INTRODUCTION

In case of generating units' faults, the operation security will be given by the maintenance of enough "short-term generation reserve" that should be appropriately activated through the frequency control, as much in quantity as in speed, to maintain the system frequency above the acceptable minimum. This frequency limit is set by international norms for the project of systems and components, and it corresponds to 95% of the nominal frequency. Otherwise, generating units will be taken out of service by their low frequency protections with the purpose of avoiding damages in turbines and of maintaining the supply to their ancillary services. This would cause the perturbation increase that leads to the system collapse.

The term "short-term reserve" is used due to its temporal response depends on the dynamic transients of the system. The access time and the actually activated reserve cannot be considered separately from the temporal system behavior. Researches in this field demand the consideration of the dynamic system behavior.

Economy is, together with security, one of the most important requirements during the operation planning of power systems. In the short-term reserve planning it represents a very important role, due to the continuous maintenance of enough reserve is accompanied by an increase of the operating costs. Not enough reserve becomes in risk of supply deficit due to the probability of fault of the generating units. This deficit is accompanied by costs corresponding to the consequences of the eventual faults.

In the common procedure of short-term reserve planning for frequency control, the operator sets a reserve power that in general corresponds to the power of the largest unit in operation. This value is based on the operation experience, and it respects at the same time the (n-1) security criterion referred to the generation. In this way, the primary frequency control units are partially loaded to guarantee the required short-term reserve. For this reason more units than the strictly necessary should be dispatched to supply the load. Because of the efficiency of the thermal units decreases in partial load, and that the additional dispatched unit has in general larger operating costs, the system operating costs are increased.

An alternative to decrease the generators reserve power and to improve the frequency control is given through the application of energy storage devices, so that the exceeding energy is stored for their use in the frequency control in substitution of the generators power reserve. Using these storage devices, jointly with new power electronics devices to control the energy input-output, could be also carried out a more efficient frequency control. Therefore, it is necessary the study and the evaluation of the nowadays-available energy storage systems that better meet the selection criteria for application in the frequency control.

II. SELECTION CRITERIA

For the evaluation of the energy storage systems it should be previously determined the kind of frequency control that will be realized. It can be carried out a continuous frequency control, in which the controller device measures the system frequency and determines control actions to maintain the frequency inside a defined range. In this operation mode, it is required that the storage system participates actively, because it will be continuously required. In this case, the storage system should have a very short charge/discharge response time, so that to allow the continuous control of the frequency deviation. These storage systems should have a charge/discharge time up to one minute, to get an efficient frequency control according to the system dynamics.

On the other hand, the frequency control could only act against greater system faults. Thereby the controller acts when the frequency deviation overcomes a defined frequency threshold wider than in the former case. In such a way the storage system will be less required, because it will be only required in few extreme cases. For this operation mode, the response times will have slightly smaller requirements. It is necessary that the storage system has also a discharge time up to one minute, but the charge time can be a little longer, up to some minutes.

Therefore, in the present work the frequency control mode that imposes slightly smaller requirements for the storage system is considered. However, this requirement should be set in agreement to the dynamics and the control mode that is used in the considered system.

To compare the storage systems under study, they were all considered with a similar power and storage capacity. The selected solution/s should meet the following conditions in order to be considered viable of using in the proposed application:

- Competitive energy costs - compared with current rates.
- Localization independent - free of geographical constraints.
- Feasibility - based on current technology.
- No environmental impacts - minimum ecological impact.
- Safety - work in environment with minimal hazards.

III. CONSIDERED POSSIBLE SOLUTIONS

A. Introduction to Energy Storage Systems

Energy storage systems used to support generation utilities has several advantages, comprising two major aspects. First, they can be used for stabilization purposes, permitting the generating units to run at a constant, stable output level, even if the load fluctuates greatly and rapidly. Second, proper amount of storage can provide energy to ride through periods when the generating unit is unavailable.

These systems use different energy storage technologies, grouped into four major approaches: store energy as chemical, electric, mechanic or thermal energy.

According to the used storage method, the energy exchanged with the storage device can be AC or DC.

Electrical and chemical storage methods exchange their energy as DC, so that the storage system should interact with the power system using power converters. These are reversible subsystems that rectify AC (rectifiers) to charge the storage devices, and they transform DC to AC (inverters) supplying the stored energy to the electrical network. The storage system is composed of three main subsystems described in Fig. 1:

- Energy Storage Device.
- Power Converter.
- Balance of Plant (BOP).

The balance of plant is designed to allow the subsystems, energy storage device and power converter be correctly operated. With this aim, additional services are required such as: environmental protection for the subsystems (housing), heating, air conditioning, auxiliary power, utility system protection, and safety systems.

Mechanical and thermal storage methods exchange their energy as AC, so that the storage system can directly interact with the power system.

This paper focuses in the determination of the most appropriate storage devices for application in the frequency control of power systems. The influence of power converter and balance of plant on the overall storage system is considered in the comparison of the different storage methods.

B. Chemical Storage Systems

1. Batteries (BES)

Two types of batteries exist: Non-rechargeable (primary) and Rechargeable (Secondary) Batteries. The last ones, which can be repetitively charged and discharged, are those used as storage devices. From now on, only this type will be considered when batteries are referred.

The batteries store electric energy as chemical energy, by using the incoming electric power flow to rearrange ions and chemical compositions of the chemicals contained in a fluid or solid electrolyte.

Batteries produce electricity, by causing a chemical reaction in the presence of an electrolyte. The released ions travel through the electrolyte creating a DC flow at a relative low voltage. Batteries are made up of individual cells connected in series, parallel, or series-parallel in order to get modules with higher voltages and currents.

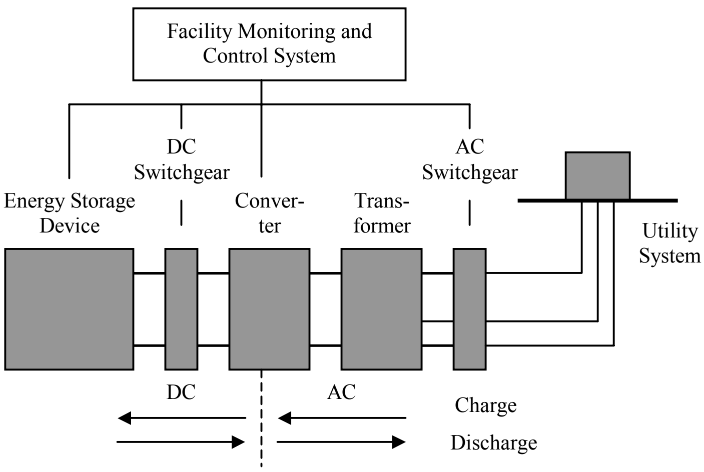

Fig. 1. Energy Conversion/Storage System by means of Chemical or Electrical Storage Devices

The following types of batteries exist:

- Lead-acid
- Alkaline
- Nickel Chemistry (Nickel-Metal Hydride, Nickel-Cadmium)
- Lithium Chemistry (Lithium, Lithium-Ion)
- Sodium Chemistry (Sodium-Sulfur, Sodium-Salt)

Table I compares the various types of battery systems designed specifically for electric power storage applications, based on statistics given in [1], and include the cost and efficiency losses of any converter systems needed.

Lead-acid batteries are the least physical-efficiency battery type, in the sense that they have the lowest energy and power densities. They generally require more room, and have more weight than other type of battery. These disadvantages are not very important for their application in the frequency control of power systems.

However, they have several distinct advantages that make them the most suitable battery type for the present application. The units are robust and safe and allows for extremely fast discharges, on the order of 5ms, but perhaps most important, they have low price and high electrical-efficiency. Measured on a levelized lifetime $/kWh of storage basis, they cost up to 1/10 of other types of batteries.

The battery energy storage system is environmentally attractive because the emissions are virtually zero, and recycling of old cell material can be done at current battery recycling stations.

The main potential problem with these batteries is its relatively short lifetime, measured in cycle life, i.e. number of cycles the battery will complete before it needs to be replaced, at 100% depth of depletion (DOD). For instance, using a new lead-acid battery, Horizon Model 12H85 of 12V, 85Ah at the 3-hour rate of discharge, a 600cycles lifetime and a cost of $130/kWh, results:

TABLE 1
BATTERY SYSTEMS FOR ELECTRIC POWER STORAGE

System attribute	**Lead-acid**	**Nickel-metal hyd.**	**Lithium polymer**	**Sodium-sulfur**	**Sodium-Salt**
Specific energy in kWh/m^3	71.43	178.57	214.28	**250**	178.57
Specific power in kW/m^3	107.14	214.28	392.86	**535.71**	**535.71**
Efficien-cy % over 24 hours	**92**	**92**	88	88	87
Life time, Deep cycles	400	800	600	**1000**	800
Cost per kWh	**$125**	$375	$550	$350	$300

- For an application of 10MWh about 9800 units will be required, that is $1.28 millions and considering an average of 4 cycles per day, 1460 cycles per year would be required. Although the batteries would not be cycled to 100% DOD, the lifetime for this application would still reach a maximum of only 1 year. Replacing this batteries every year, at this cost is not considered economical.

Therefore, this large continuous cost is the primary reason for eliminating the battery systems as a viable alternative for the present application.

One other possible problem is the time the system takes to charge the battery. With current battery technology, the time it takes to charge a battery to 100% is about three hours. In the near future, charging times could be decreased with some of the newer battery technologies currently being developed

2. Fuel Cells (FC)

In principle, a fuel cell operates like a battery. It generates electricity combining hydrogen and oxygen chemically without any combustion. Unlike the batteries, a fuel cell is not run down neither it requires recharge. It will produce energy as electricity and heat as long as fuel is supplied. The only by-product that is generated is water 100% pure.

Different types of Fuel Cells exist, such as: Phosphoric Acid (PAFC), Proton Exchange Membrane or Solid Polymer (PEM), Molten Carbonate (MCFC), Solid Oxide (SOFC), Alkaline and others.

This storage system uses the following two methods to store energy:

- Fuel Cells and hydrogen cycle: It is used an electrolysis process to obtain the hydrogen.
- Reversible or regenerative fuel cells: These fuel cells can revert their process producing hydrogen and oxygen directly, if a current flows in reverse way through them.

The fuel cell system would have a long life span due to the fact that it doesn't have many moving parts. This solution would be environmentally safe; it only produces water, electricity, hydrogen, and oxygen. Some disadvantages of this system are that hydrogen and oxygen (in their pure form) are highly flammable and that the electrochemical materials involved are expensive. But, a significant problem is its low efficiency (worst than 80% for storage and 50% for re-generation). In the electrolysis process high losses in the form of heat are produced because of the huge amount of current required to generate enough hydrogen.

Other important part of this process is the compressor that put the hydrogen in a high-pressure state (2100kg/m^2). The lifetime of the compressors would be far less than that of the fuel cells and electrolysis. They would need regular maintenance and eventual replacement. These reasons make this system not suitable for the current application.

C. Electric Storage Systems

1. Superconducting Magnetic Energy Storage (SMES)

SMES systems store electric energy in the magnetic field generated by a DC current flowing through a superconducting magnetic coil. Because the coil has no internal resistance, the energy is not dissipated as heat. For that reason it is stored in a "persistent" mode, virtually indefinitely, until it is required. This energy is released using the reverse process when it is needed. The described basic principle is depicted in Fig. 2.

The potential overall efficiency of these systems is very high. Furthermore, as the Superconducting coil has no resistance, response to both recharging and discharging is limited only by the switching time of the solid-state components doing the DC/AC conversion.

The superconductor needs to be maintained at liquid helium temperatures (less than -268.93°C) in order to sustain superconducting properties. High temperature superconductors (HTS), those that operate at liquid nitrogen temperature (between -209.86°C and -195.8°C) or above, allow reduced capital and operating costs, but at this time helium temperatures are still needed to prevent quenching of the HTS, i.e. the heating of the superconducting material above the temperature of zero resistance. This can either occur to the coil as a whole or in a small point in the coils' material.

SMES systems have the problem that they require a set of compressors and pumps to maintain the liquid coolant at a low temperature, making them complicated and in need of relatively frequent maintenance. However, current systems have shown good levels of reliability. Also, they have a DC to AC converter system with a truly phenomenal control capability.

These systems have several inherent advantages. They are silent, efficient, and very reliable. And, they have the best power control capability of any electrical equipment, getting near the perfect power quality.

SMES is an expensive way to store power, but meet all the set criteria for the application in the frequency control of power systems. It is expected that the cost will be reduced in the next years.

2. Supercapacitors or Ultracapacitors (SES)

A capacitor stores energy through the conservation of an electric field between two electrically conducting plates. This electric field will be preserved until the stored energy is released by applying a load to it.

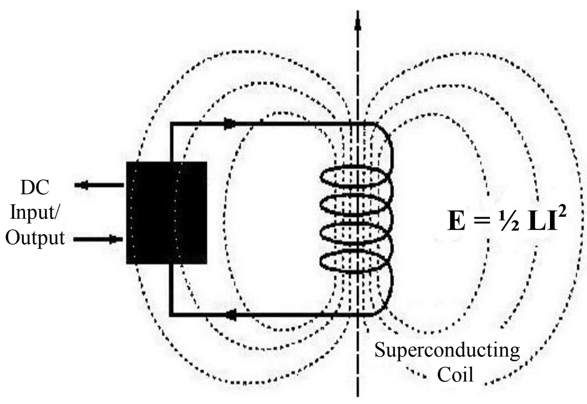

Fig. 2. Operation Principle of the Superconducting Magnetic Energy Storage (SMES)

The so-called "Supercapacitors" have from 20 to 1000 times the energy storage capability of traditional capacitors. These devices store a relatively modest energy compared with the batteries, but they can release it very quickly.

For this reason they are used as "acceleration batteries" in several prototypes of new generation electric vehicles (EV).

The high ratio of power density to energy density, the robustness and the immunity from cycling impact on lifetime, makes the supercapacitors are considered the best option to handle with quick fluctuations of load peaks of very short duration.

The ultracapacitor system has the potential to be the best system using size considerations. They are currently available with energy densities of 4000Wh/m^3. Theoretically, these capacitors can have energy densities of around 20.000Wh/m^3 using advanced materials. Such a system for a 400MW requirement would only need a volume of 20.000 m^3, or approximately 27x27x27m. Also, these systems have an incredible lifetime (better than 100.000 cycles o 68 years).

Ultracapacitors have several great advantages, which make them almost unbeatable for the application in the frequency control of power systems. They have no moving parts, require neither cooling nor heating, and undergo no internal chemical changes as part of its function. As a result, they are simple and robust, requiring practically no maintenance, and they have a service lifetime measured in decades, with no lifetime degradation due to frequent and deep cycling. While energy density is relatively low, the power density of capacitors is extremely high: they can release all their power nearly instantly.

Unfortunately, the ultracapacitors are relatively new and expensive, but meet all the set criteria for the present application.

D. Mechanical Storage Systems

1. Hydroelectric (Pumped hydro)

An energy storage method using pumped hydro is very popular, and it has been widely proven over many years (60-70 years). Often it is used to smooth the peaks in the daily demand curve of electric power systems. Thereby, two water reservoirs or lakes at different elevations connected by a pump/generation station are used. During the night, water is pumped from the lower reservoir to the higher one using electric pumps. By that time the energy is obtained at low cost from the electric utility. During the day by the great demand peaks, water flows from the upper reservoir to the lower one, so that power station generates energy and it is delivered to the utility grid. The overall efficiency of these systems is usually better than 80%, but their applicability depends obviously on the geographical conditions. An important problem of these systems is the large amount of land area they require, which alters the local environment due to need to impound a large volume of water. Also, the response time is not appropriate for the application in the frequency control.

2. Flywheels (FES)

FES systems store electric energy as kinetic energy. The flywheel consists of a ring that rapidly spins on a magnetic bearing, inside a vacuum chamber. The energy is stored as kinetic energy of the rotating masses, which have very low rotational losses. This is because the magnetic bearing prevents the contact between the stationary and rotating parts, minimizing the friction. In addition, being the system in vacuum, the aerodynamic resistance of the flywheel is decreased, allowing getting high efficiencies of the overall system.

Because the stored energy is directly proportional to the mass of the flywheel, and square proportional to the rotational speed, increases in rotational speed yield in a large benefit for the energy density. The following two types of flywheel are used:

- High-speed flywheel
- Low-speed flywheel

Conventional magnetic bearings have the disadvantage that they consume power, which is dissipated as heat in the copper electromagnets. A reasonable magnetic bearing consumes a few watts for each kilogram of flywheel weight, depending on the structure of the bearing and the control system.

Superconducting magnetic bearing, on the other hand, have demonstrated losses of 10^{-2} to 10^{-3} watts per kg for a 2000rpm rotor. This leads to an overall efficiency of 90%.

Flywheels are efficient energy storage devices due to de lack of touching parts and the vacuum in which the flywheel is spinning. The lifetime of flywheels is estimated about 40 years. They also have high energy densities, which means that less material is required to build an energy storage facility.

A big disadvantage of using flywheels is the fact that they constitute a new technology that has not been widely implemented.

Flywheel systems meet all the specified criteria for this application.

3. Compressed Air (CAES)

CAES systems use electric power to run compressors that pushes air into a tank at very high pressure. When the stored energy is required the compressed air is released, expanded and sent to the turbine, which is coupled to an electric motor/generator. To have a volume of appreciable storage, large underground tanks are used.

One problem with CAES is the inability to respond quickly. The response time is in order of several minutes. This poor response time can be overcome by combining more than one energy storage system, which can enhance the overall system efficiency and provide more flexibility. Another problem is that for compress air systems to be cost effective there needs to be an underground cavern available for storage of the air. This indeed is a problem since the storage system needs to be location independent. Also the use of underground caverns, if available, would disrupt the ecosystem.

This technology is well established and developed, but is not suitable for the considered application.

E. Thermal Storage Systems

1. Water Heating

These systems store energy as super-heated oil or molten salts. The electric power is used to heat the salt or oil at very high temperatures (between 316°C and 594°C) and then it is placed in large tanks (from about 3 m to 16 m in diameter and 6 m high). The heat of the salt or oil is used for steam generation and then to run a turbine coupled to an electric motor/generator. Most of these systems store energy for up to 20 hours required by maximum power.

These thermal storage systems will not be useful for their application in the frequency control due to the specifications to meet. The conversion losses from electrical to thermal and back again to electrical are too great for this option to be viable.

IV. CONCLUSIONS

Energy storage systems always involve trade-offs among a number of factors in performance, the most important being storage capability, power output level, service lifetime, and cost.

All the described storage methods have been evaluated for their application in the frequency control of the power systems using the specified selection criteria. Only three energy storage systems meet all the set criteria. They are the following ones:

- Superconducting Magnetic Energy Storage (SMES)
- Supercapacitors or Ultracapacitors (SES)
- Flywheels Energy Storage (FES)

These systems have been compared, and the results exposed in Table II.

As it is shown, the selected energy storage systems have the disadvantages that they are a new technology, not widely proven. Furthermore, they are expensive and very complex. However, current systems have shown good levels of reliability and safety, and low rates of maintenance.

It is expected for the future to reduce the cost of these systems and to improve the materials used to manufacture them. Also, the continuous research in the EV applications, will allow getting lower cost, higher power and longer lifetime battery systems. Consequently, it could be feasible to use them for the considered application in the near future.

A later analysis considering the selected storage systems, the used frequency control mode and the interacting power system, will lead to a single solution.

By considering the set frequency control mode, the costs of systems and the required performance imposed, the authors believe that Superconducting Magnetic Energy Storage Systems are currently most adequate for the present application.

TABLE II
ENERGY STORAGE SYSTEMS THAT MEET THE SET CRITERIA
FOR THEIR USE IN THE FREQUENCY CONTROL

	SUPERCAPACITORS	**SMES**	**FLYWHEELS**
Analysis of Costs:			
- Initial	$ 250 Millions	$ 0,6 - 2,4 Millions	$3 Millions
- Long Term	Negligible		
Efficiency	> 90%	~ 95 %	~ 90 %
Lifetime	>68 years (> 100.000 cycles)	> 50 years	~ 40 years
Environmental Risk	Toxic Materials	Large Magnetic Fields	None
Security	Toxic Materials	Liquid Helium	Rotating Mass at high speed
Response Time:			
- Charge	~ µs	~ 10 ms	minute
- Discharge	~ µs	~ ms	minute
Active Power	1 MW	1 MW	1 MW
Specific Energy	2 a 20 Wh/kg		100 a 200 Wh/kg
Total Energy	6 MWh	6 MWh	6 MWh
System Size	537 m^3	62 m^3	10,4 m^3
Feasibility	New Technology	New Technology	New Technology
Future	Cost Reduction Larger Systems	Cost Reduction Larger Systems	Cost Reduction Higher Material Strengths

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