UTILIZATION OF ENERGY STORAGE SYSTEMS

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ABSTRACT

This paper deals with utilization of energy storage systems. The shape of the daily consumption diagram, its weekly and seasonal diversification and their statistical features depend on the behaviour of the different consumer groups. In an electricity power system based on thermal, nuclear, hydro and renewable generation, the storage systems will find a wide field of application and may perform various duties, which must be taken into consideration in order to gain the largest possible advantage in optimization of the supply side.

1. INTRODUCTION

The diversity of applications of electricity and particularly the fact that some of its uses, such as lighting and space heating, are subject to substantial seasonal variation makes the economic ideal of supply for constant consumption throughout the year unrealistic. Generation itself cannot, in any case, be constant because of fluctuations in hydroelectric generation and intermittency of renewable sources.

There should therefore be the specially structured unit between producer and customer which can co-ordinate them. This unit has to provide the following two possibilities:

- from producers, to transfer generation or production capacity from off-peak to peak load hours to supplement the development of specific peak-production means,
- from distributors or customer, to encourage customers to shift peak hour consumption requirements to off-peak times. Incidentally, the customer can also alter his/her habits.

It is useful define this new structural unit as the energy storage.

2. THERMAL ENERGY STORAGE

Direct storage of heat in insulated solids or fluids is possible even at comparatively low temperatures (theoretically from $\vartheta > 0°C$), but energy can only be recovered effectively as heat. Hot rocks and fireplace bricks have served as primitive heat storage devices from ancient times. This is still the case in industrial furnaces and in the baker’s electric oven, where cheaper electricity is used to heat the oven during the night.

High temperature thermal storage can be used both to utilise heat in industrial processes and for heat engines. One recent example is the power supply for Stirling engines [2].

Thermal energy storage (TES) is ideally suited for applications such as space heating, where low quality, low temperature energy is required, but it is also possible to use TES with conventional coal- and nuclear-fired power plants which dominate the installed capacity of electricity utilities and are likely to continue to do so for the near future.

It is natural to ask why, instead of passing energy through several conversion stages, not just store primary heat from a base-load plant’s boiler and recover it when it is most needed?

Thermal energy storage differs from other storage forms for power generation in that energy is extracted in the form of steam between the boiler and turbo-alternator. Other storage forms are generally charged by extracting the energy as electricity. A power plant used to transfer the heat can be run under constant conditions, independent of electrical demand, since the stored heat can be used to satisfy its fluctuations and the required energy will be readily available to meet load fluctuations swiftly. Using thermal storage, the boiler can be operated at a constant power level corresponding to the average power output of the base-load plant. The value of storing excess power from a base-load plant during a charging period at night and releasing it during the day has already been shown. Indeed, load cycling of large coal or nuclear plants can be avoided, maximising the return from these expensive plants and providing improved reliability and reduced maintenance.

Heat can be transferred to the store fluid by heat exchangers using steam extracted ahead of and between the turbines, thereby reducing the plant’s electrical output. This charging mode is implemented during periods of low electrical demand.

Nuclear- and coal-fired plants are sources of thermal energy. Within them, the thermal energy source can be one of the following:

- High-pressure (HP) turbine inlet steam
- Intermediate-pressure (IM) turbine inlet steam
- Low pressure (LP) turbine inlet steam
- Intermediate steam-extraction point and feedwater heater (FWH) outputs in the FWH system to raise condensate back to boiler inlet temperature.

The obvious thing to do is to store some energy to increase the flow of steam to the feed heaters at the expense of flow to the condenser, and to use the additional thermal energy of the feed heaters to provide additional hot water, which can itself be stored [1], [3], [5].

3. FLYWHEEL STORAGE

Storing energy in the form of mechanical kinetic energy (for comparatively short periods of time) in flywheels has been known for centuries, and is now being considered again for a much wider field of utilisation, competing with electrochemical batteries.

In inertial energy storage systems, energy is stored in the rotating mass of a flywheel. In ancient potteries, a kick at the lower wheel of the rotating table was the energy input to maintain rotation. The rotating mass stores the short energy input so that rotation can be maintained at a fairly constant rate. Flywheels have been applied in steam and combustion engines for the same purpose since the time of their invention. The application of flywheels for longer storage times is much more recent, and has been made possible by developments in materials science and bearing technology.

The energy capacity of flywheels, with respect to their weight and cost, has to date been very low, and their utilisation was mainly linked to the unique possibility of being able to deliver very high power for very short periods (mainly for special machine tools) [1].

The energy content of a rotating mechanical system is:

$$W = \frac{1}{2} \cdot I \cdot \omega^2 \tag{1}$$

where I moment of inertia,
ω angular velocity.

4. PUMPED HYDRO STORAGE

We have more than a century of experience in the storage of natural inflows as an essential feature of the exploitation of potential hydraulic energy. Reservoirs can be used to store artificial inflows obtained by utilising the energy available in power systems during demand troughs from generating capacity that is not fully loaded.

At the start of this century, all hydroelectric plants with reservoirs were equipped with certain pumping mechanisms in order to supplement the natural inflow to the upper reservoir; the main idea was to create seasonal storage in a hydroelectric power system.

Pumped hydro storage is the only large energy storage technique widely used in power systems. For decades, utilities have used pumped hydro storage as an economical way to utilise off-peak energy, by pumping water to a reservoir at a higher level. During peak load periods the stored water is discharged through the pumps, then acting as turbines, to generate electricity to meet the peak demand. Thus, the main idea is conceptually simple. Energy is stored as hydraulic potential energy by pumping water from a low-level into a higher level reservoir. When discharge of the energy is required, the water is returned to the lower reservoir through turbines which drive electricity generators.

Pumped hydro storage usually comprises the following parts: an upper reservoir, waterways, pump, turbine, motor, generator and a lower reservoir, shown schematically in Fig. 1.

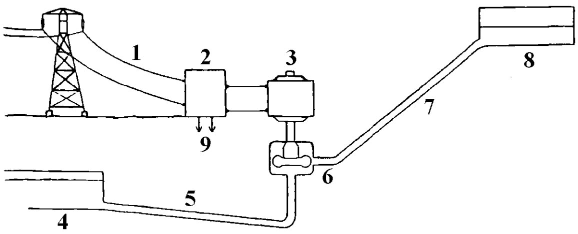

Figure 1 - Pumped hydroelectric energy storage (1 transmission; 2 transformer; 3 motor-generator; 4 lower reservoir; 5 tail race; 6 pump-turbine; 7 penstock; 8 upper reservoir; 9 to loads) [1].

5. COMPRESSED AIR ENERGY STORAGE

Storage of mechanical elastic energy has been widely used from prehistoric times in various mechanisms for producing limited amounts of energy, particularly in weapons (the bow and arrow, for example). The application of elastic energy storage in the form of compressed air storage for feeding gas turbines has long been proposed for power utilities; a compressed air storage system with an underground air-storage cavern was patented by Stal Laval in 1949. Since that time, two commercial plants have been commissioned; HuntorfCAES, Germany and, very recently, McIntosh CAES, USA.

The return to the power system of electrical energy stored in intermediate form has to be linked with an energy-conversion process from a primary source. In this case, compressed gas is the medium which allows us to use mechanical energy storage. When a piston is used to compress a gas, energy is stored in it which can be released when necessary to perform useful work by reversing the movement of the piston. Pressurised gas therefore acts as an energy storage medium [1], [4].

6. HYDROGEN AND OTHER SYNTHETIC FUELS

Synthetic fuels are considered to be substitutes for natural gas or oil and are made from biomass, waste, coal or water. Production of these fuels demands energy which cannot be obtained from base-load power plants during off-peak hours. Synthetic fuels are a type of energy storage, therefore, since it is possible to use them instead of oil or gas for peak energy generation. The fuels themselves are only a type of medium; as with any other storage concept, a power transformation system and central store are also required. Storage media have to be produced during off-peak hours in a chemical reactor or electrolyser-they have to be considered as a part of a power transformation system used during the charge regime.

During the discharge regime, the storage media have to be converted into electrical energy, using any kind of thermal plant with an appropriate combustion chamber. These storage media have to be stored in a special containing device, a central store. The use of synthetic fuels does impose some problems of safety and container material, but is not very different from the infrastructure of storage and distribution systems involving natural gas and oil fuels [1].

7. ELECTROECHEMICAL ENERGY STORAGE

The most traditional of all energy storage devices for power systems is electrochemical energy storage (EES), which can be classified into three categories: primary batteries, secondary batteries and fuel cells. The common feature of these devices is primarily that stored chemical energy is converted to electrical energy. The main attraction of the process is that its efficiency is not Carnot-limited, unlike thermal processes. Primary and secondary batteries utilise the chemical components built into them, whereas fuel cells have chemically bound energy supplied from the outside in the form of synthetic fuel (hydrogen, methanol or hydrazine). Unlike secondary batteries, primary batteries cannot be recharged when the built-in active chemicals have been used, and therefore strictly they cannot be considered as genuine energy storage. The term “batteries”, therefore, will only be applied for secondary batteries in this section.

Batteries and fuel cells comprise two electrode systems and an electrolyte, placed together in a special container and connected to an external source or load. These two electrodes, fitted on both sides of an electrolyte and exchanging ions with the electrolyte and electrons with the external circuit, are called the anode (–) and cathode (+) respectively.

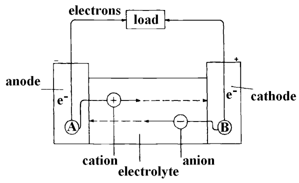

Figure 2 - Electrical energy source during discharge [1].

The anode is defined as the oxidising electrode; i.e. the electrode which is sending positive ions into the electrolyte during discharge. When supplying positive charges to the electrolyte, the anode itself becomes negatively charged and therefore may be considered as an electron source for the external circuit. At the same time, the cathode consumes electrons from the external circuit and positive ions from the internal circuit. To maintain electric current in the external circuit, electrons have to be produced at the anode and used up at the cathode. Since no chemical process can generate electric charge, the transport of charge in the electrolyte (in the form of ions between the electrodes) has to take place at the same time.

It should be mentioned that no electron conductivity must take place, in that case, the battery will discharge itself through a short circuit.

The electromotive force (EMF), of a battery, which initiates the electric current, is the difference between the electric potential of the electrodes. The terminal voltage U equals the electromotive force minus the voltage drop in the battery due to its internal resistance R, which contains frequency and time dependent components associated with the electrolytic processes, ohmical resistance against the charge transport in the entire internal circuit components, an external load dependence component and the remaining energy contents of battery component. In other words, the internal resistance can be described in the form of a rather complicated impedance. The smaller the value of internal resistance the lighter is a battery’s turnaround efficiency, since there is a linear dependence between thermal losses in a battery and its internal resistance.

High reaction rate and good transport conditions will lead to a substantial decrease in the irreversible thermal losses in any electrochemical battery. Both factors can be met by working at high temperatures and with chemically active electrodes. In both cases the electrolyte will be a limiting factor owing to problems of stability and transport properties.

A common solution is to use different types of aqueous electrolytes, but unfortunately they can only work at high temperatures under substantial pressure, therefore requiring special vessels. The use of ceramic materials, which have a suitably high specific conductivity for ions able to take part in the electrochemical process, is a promising possibility. The development of these so-called solid-state ion conductors has contributed to a breakthrough in battery technology [1], [4].

8. CAPACITOR BANK STORAGE

Energy can also be stored in the form of an electrostatic field. Let us consider an electrical capacitor, i.e. the device which can collect electric charge which is establishing an electric field and hence storing energy. The capacitance C of a capacitor is defined by the amount of charge Q it can take up and store per unit of voltage:

$$C = \frac{Q}{U_c} \tag{2}$$

where U_c is the voltage of the capacitor.

As an example, let us take a plate capacitor with plate area A and distance d between its plates.

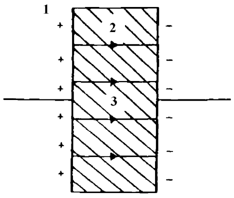

Figure 3 - Parallel plate capacitor (1 capacitor charge; 2 electric field; 3 dielectric material) [1].

From the definition of capacitance it follows that the capacitance of the capacitor is:

$$C = \varepsilon \cdot \frac{A}{d} \tag{3}$$

So-called dielectric materials can be polarised and, if used as a medium, the total charge stored in a capacitor using such a material will be increased.

The properties of this medium may be described by the constant ε called the permittivity, which is measured in farad/m since both A and d have metres as the basic unit. The electric field E is homogeneous inside the plate capacitor only when tile distance between the plates is small. In order to keep the charges at the plates divided, and thereby to maintain the electrostatic field, the dielectric medium must have a low electronic conductivity; so we are looking for dielectric materials with high permittivity [1], [4].

9. SUPERCONDUCTING MAGNETIC ENERGY STORAGE

Completely novel, based on the development of superconductors, is the possibility of storing significant quantities of energy in magnetic fields. Let us consider a series *RL* circuit, a simplified diagram of superconducting magnetic energy storage (SMES), as shown in Fig. 4. Here R is the total resistance of the electrical circuit between the source of the power supply of voltage U and the magnetic coil of self inductance L. The total resistance comprises the internal resistance of the source and resistance of the coil. When a coil is connected to a constant voltage source, the electric current varies with time: it is zero at $t = 0$ and it stabilises at I_{max} when the magnetic field has been built up. If the switch in Fig. 4 is closed, the transient storage process will start and electrical current $i(t)$ through the circuit will rise during charging and fall during discharging. The transient process equation may be written as follows [1]:

$$i(t) = \frac{(U + U_i)}{R} \tag{4}$$

where U_i is the induced electromotive force (EMF)

$$U_i = -L \cdot \frac{d\,i(t)}{d\,t} \tag{5}$$

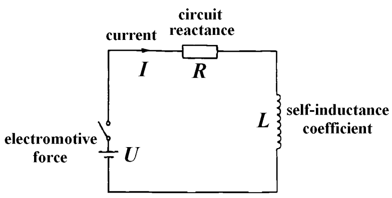

Figure 4 – Series *RL* circuit [1].

10. CONCLUSIONS

In summarising the information it is necessary to review the status of large scale electrical energy storage and to make a comparison of storage plants with very different characteristics, as well as considering conventional alternatives.

The main feature of mentioned kinds of storage, being series-connected to the system, is that they react immediately to any change in load demand, providing an adequate power response. If the frequency deviation exceeds that permitted by the power system’s regulations, the steam governor opens or closes the valves and additional energy is extracted from, or supplied to, the enthalpy of the steam in the thermal power station’s boilers. There is enough thermal energy stored in the boilers to cover changes in load demand for a few minutes, so the power system, is able to act as a thermal store.

To summarise the above, a power system has an ability to act as a capacitor, magnetic, flywheel or thermal energy storage device without additional investment; generators play the role of power transformation systems, while thermal equipment, rotating machinery and transmission lines play the role of a central store. The capacities of these stores are limited, however, and therefore the power system’s built-in storage can only accommodate short time fluctuations in load demand.

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