

STORAGE OF ELECTRICAL ENERGY

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Summary

Energy consumption has been steadily increasing, causing concerns about exploring alternative energy sources. While finding new and efficient sources of electrical energy is an important task, finding ways to store it is equally important.

Superconductive Magnetic Energy Storage (SMES) coils, batteries and capacitors are three important energy storage devices that store the energy in magnetic, chemical or electrical forms, respectively.

SMES systems are economical at very high power levels. Batteries have the largest spectrum of application areas; they are used in many portable electronic devices and in automobiles, as well as the power systems. Conventional capacitors have smaller energy densities, and therefore are used only in low to medium power applications. A new type of capacitors, called ultra capacitors, promises to fill the gap between the capacitors and batteries.

This work presents an overview of all these systems, defines the principles of operation, and explains the structures and different types along with the application area. A brief comparison is given at the end of the work.

1. Introduction

Energy demand from the consumers is not constant but varies by time. There are high and low demand periods during the day. There are also great variations in demand over each year. In order to meet the demand in the most proper way, some of the generating plants are operated continuously while some of them are used only when there is need for them. Base load generation which is approximately 45 per cent of the peak power is provided by large coal or nuclear power plants. Starting of these plants takes longer times, and therefore they work continuously. Hydroelectric power plants can quickly get started, and therefore they are cycled in and out of service as power demand changes from 45 per cent to 85 per cent of the peak demands. The remaining 15 per cent is supplied by gas turbines.

Gas turbines are costly systems. They require special fuels, and their maintenance is difficult. Therefore, alternative solutions are necessary. The most proper alternative seems to be storing the excess generated energy when the demand is below the base line in a storage system, and to deliver this energy during the peak demand periods.

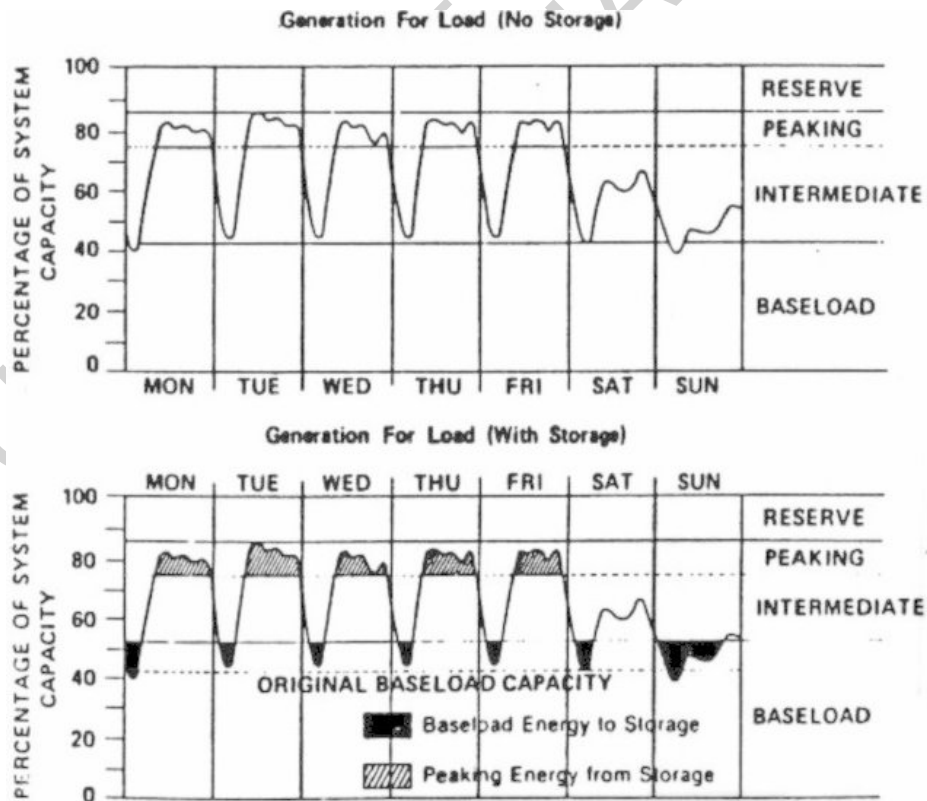


Figure 1: Typical Weekly Load Curve of an Electric Utility

Figure 1 shows a typical weekly load curve of an electric utility. In the upper part, it is assumed that there is no storage system and the peak demand is met, as previously mentioned, by gas turbines or other means. In the lower part of the figure, the shaded regions below the base line show the periods of energy storage, and the shaded regions around the peak demands show when the stored energy is delivered, without a need for increasing the base load capacity or using gas turbines.

The energy storage systems that could be used for this purpose are pumped water systems, batteries and superconducting magnetic energy storage systems (SMES). In pumped water systems, water is pumped into a water reservoir located in a high place during the low demand times, and it is used to generate energy when there is demand. Batteries store the energy as chemical energy, and delivers DC power when needed. SMES coils store the energy in their magnetic field, and deliver it in DC form when needed. Both batteries and SMES systems, thus, need power converters to convert the energy into AC form.

This work covers the batteries and SMES coils in detail. Also included in this work is the capacitor that can store energy in its electrical field. Capacitors of various sizes are used in many different applications to store energy.

2. Batteries

Batteries are devices that convert chemical energy into direct current (DC) electrical energy. Batteries store the energy in chemical form. This stored energy is converted to electrical energy whenever desired, and this conversion is a clean and silent process since it does not require any moving part. The process of converting chemical energy into electrical energy is called discharging.

A battery consists of two or more voltaic cells. Voltaic cells can be divided into two groups: primary cells and secondary cells. Primary cells are also named as fuel cells or un-rechargeable cells. Other names given to secondary cells are accumulator or storage cells. Accordingly, batteries are named to be primary or secondary (storage) batteries. In primary batteries, energy conversion is irreversible. While the chemical energy is being converted into electrical energy, some of the material is used and this material can not be replenished. When all the energy is converted, the battery becomes useless. On the other hand, energy conversion in storage batteries is reversible. A discharged battery can be returned to its original state by passing a current through it in the direction that is opposite to that of the discharge current.

Most common examples of primary and secondary batteries are dry cells and lead-acid batteries, respectively.

2.1. Principle of Operation

All the batteries contain three basic components; a positive electrode (cathode), a negative electrode (anode) and an electrolyte, which is usually in liquid form. The electrolyte must have ionic conductivity. The anode provides the electrons (donor) while the anode collects them.

These electrodes are of different kinds, and when immersed in the electrolyte, they display their own characteristics. The cell voltage is equal to the difference between the potentials of these electrodes, and it rarely exceeds 2 V. By connecting several cells in series, any desired voltage can be obtained.

The most common type of anode is zinc, although alkali metals such as lithium and sodium are the most effective ones. The most effective cathodes are fluorine, chlorine, oxygen, sulfur and metal oxides.

The Leclanché cell, which is also called the zinc-carbon dry cell, is the most familiar primary cell, and therefore it is a good idea to describe the operation principles of battery cells on these types of cells.

They are mostly used in flashlights and portable radios. Zinc forms the negative electrode, and a graphite rod is the positive electrode. The graphite rod is surrounded by a densely packed layer of graphite and manganese dioxide. The electrolyte is a moist powder containing zinc chloride.

Figure 2 shows the principle structure of a Leclanché cell. In the figure, a load is also shown to be connected between the positive and negative electrodes. Therefore electrons find a path to flow, and the battery discharges. The electrochemical reactions that take place during the discharge of the battery are combined reduction-oxidation reactions.

The electrical current is from the cathode to the anode through the externally connected load. As a result of the electron flow, the anode is oxidized, and the cathode is reduced. Inside the cell, anions (negative ions) flow to the anode while the cations (positive ions) flow to the cathode. When the battery is new, it produces a potential difference of 1.5 V. Leclanché batteries can not be recharged or used again once they are discharged.

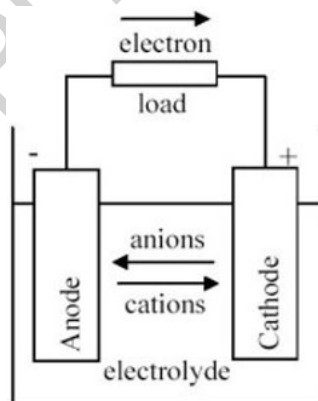


Figure 2: Principle Structure of a Leclanché Cell

While primary batteries can not be used again after it is discharged, secondary batteries can be recharged and used. In order to regenerate the depleted electrodes, a voltage that is greater than the original voltage of the battery is applied across the battery in the opposite direction. Positive terminal of the external power source is connected to the

anode while the negative terminal is connected to the cathode. As a result, a current in the opposite direction to the discharge current is established. Electrons are released from the anode to the external circuit, and positive electrode (cathode) gains these electrons.

2.2. A Brief History

The first batteries are believed to be built about 2000 years ago by Parthians in Mesopotamia. This was discovered by a German archaeologist, Wilhelm König at Iraq Museum in the late 1940s. These batteries consisted of thin sheet copper soldered into a cylinder 1.125 cm long and 2.6 cm in diameter. The solder was a 60/40 tin-lead alloy. The bottom of the cylinder was a crimped-in-copper disk insulated with a layer of asphalt. The top was closed with a one-hole asphalt stopper, through which projected the end of an iron rod. It was cemented into a small vase to make sure that it would remain upright.

The copper-iron combination of these first batteries is the same as that Luigi Galvani used in his galvanic cell in 1786. Later, the voltaic pile of unlike metals in contact with an electrolyte was developed by Alessandro Volta between 1798 and 1800. He also connected them in series to obtain larger voltages, and used larger areas of metal for greater currents. He designed a system called “crown of cups” that consisted of a group of cups containing salt water, arranged in a circle, and connected to each other by conductors with terminating electrodes of zinc and silver. The systems that were built by Volta were not practical since they were bulky and had strange configurations.

J.F. Daniel produced his primary cell in 1836 by using copper and zinc. He placed his electrodes in different compartments, separated by a porous partition of pot. This was followed by the works of W. Groove who discovered the practical gas electrodes, and Bunsen, who replaced Groove’s platinum electrode with a carbon cathode. This way, he was able to obtain a 2-V open-circuit voltage from the cell.

In 1859 lead-acid battery was developed by Plante. In 1868 Georges Leclanché introduced a cell which can be accepted to be the forerunner of today’s batteries. The dry cell (zinc-carbon cell) is still referred to as Leclanché cell. Only one liquid material, an ammonium chloride (Sal ammoniac) solution, was used in this cell as the electrolyte, instead of the previously used acid electrolytes. The depolarizing solution was replaced by a dry mix composed of manganese dioxide and carbon. A carbon bar imbedded in the center of the mix served as a current collector and a positive electrode. The Leclanché cell had higher electromotive force, but was still restricted to laboratories and fixed installations because of its liquid content.

Dr. Carl Gassner developed the first true dry cell between 1886 and 1888. His cell used a paste electrolyte composed of zinc oxide, Sal ammoniac, and water. The resulting cell was portable and adaptable to varying space requirements. It was also possible to connect several of them to obtain higher voltages. Therefore, it was practical to manufacture these cells, and they soon became available commercially.

T. A. Edison in the USA and Waldemar Jungner in Sweden laid the foundations of the nickel-cadmium and nickel-iron alkaline storage batteries between 1895 and 1905.

Other alkaline batteries were produced later on. The first practical silver-oxide/zinc cell was produced in 1930 by André. There have been many developments since then, and batteries are still the most widely used source of electrical power.

2.3. Need for Batteries

Batteries are used to provide the necessary power for lighting and other purposes when there is a failure in the main power system, or if the equipment requiring power is away from the main electricity supply. They are also used to supply energy to the power system in high demand periods. Especially with the development of semiconductor devices, many portable electronic devices requiring DC power has been produced. The small radio receivers, calculators, watches and flashlights are only a few to name. Batteries are also used in all automobiles. Recently there has been a great demand for uninterruptible power supply (UPS) systems to protect sensitive systems such as computers and medical equipment against power outages or fluctuations. All UPS systems have batteries. Greater demand for the batteries is expected in the near future as the research has been increasingly continuing on electrical vehicles.

2.4. Elementary Cell Performance

The most basic limitation of the electrochemical cells comes from the ability to transfer the ion current through the electrolyte. There may also be some other current limiting factors at the surface of the electrodes. Electrodes must provide large surface areas for the current to flow. For this purpose, usually, porous, solid sponge like metals, are used. Design of the cell configuration and the power density of the cell are determined by the current capacity of the cell.

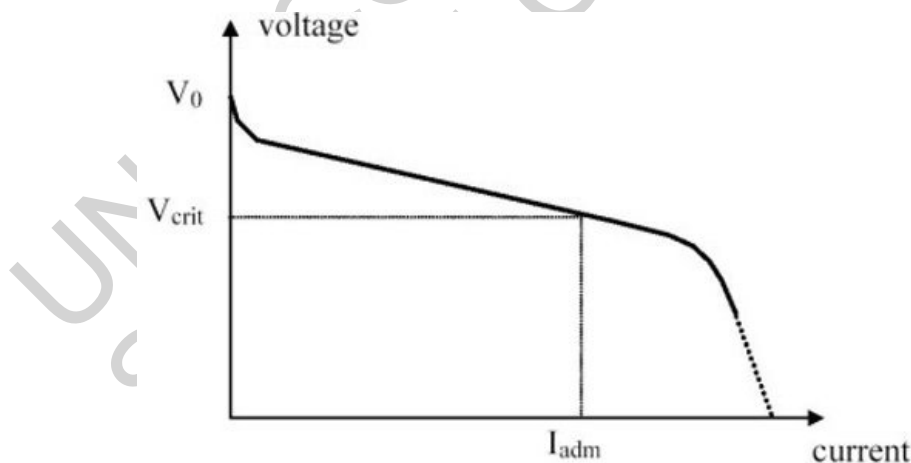


Figure 3: Typical Current-Voltage Curve of a Battery

The open circuit voltage (OCV) of a cell depends on the electrochemical system used, but it is also affected by the electrolyte concentration, gas pressure, degree of discharge of the cell, temperature, and other effects. During discharge, the cell voltage varies as a function of the discharge current. A typical current-voltage curve of a battery is shown in Figure 3. Due to the nonlinearity of the curve, the effective internal resistance is not constant but changes with varying current. At the beginning of the discharge, usually a

steep drop is observed at the voltage. After 3 to 10 per cent of the initial capacity is delivered, a more stable voltage is obtained. At the end of the discharge, the voltage may fall very sharply. Therefore, it may be necessary to terminate the discharge at a certain level even though the reactants are not yet completely consumed. The current labeled as I_{adm} is the highest admissible current for the cell. This also corresponds to critical lower bound voltage V_{crit} . There is also a related power limit defined for the cell. It should also be noted that, higher current levels may be admitted if short duration pulsed loads are applied.

The discharge current of a cell depends on the externally connected load resistance. Depending on the load, four different discharge modes may be distinguished:

- Constant external resistance. Current falls off as voltage decreases.
- Constant current discharge.
- Constant power discharge.
- Variable load discharge with prescribed load variation profile.

Each cell type is characterized by its rated mode. The average voltage during discharge is referred to as the rated voltage of a given cell.

The electric charge (Q) that passes through the external circuit during the total discharge period (τ) is given by the following equation.

$$Q = \int_0^{\tau} I \tau \, dt . \quad (1)$$

If the discharge current is constant, then the equation gets simplified to

$$Q = I \tau \quad (2)$$

Although the unit of the charge is Coulombs, the amount of charge calculated in (2) is referred to as the Ampere-hour (Ah) capacity of the battery, and designated with C . The discharge rate of a battery, that is, the current which is necessary to completely discharge it in X hours, is defined to be C/X . Another parameter that is used to define the capacity of batteries is the specific energy. Specific energy of a battery is the amount of energy a battery stores per unit mass at a specified discharge rate.

This is also called gravimetric energy density. The specific energy is measured in watts per kilogram (Wh kg^{-1}). Some of the other terms used to define the capacity of batteries are volumetric energy density (Wh L^{-1}), specific power (W kg^{-1}), and volumetric power density (W L^{-1}).

The specific energy is especially important for batteries when the weight is an important concern, such as in the electric drive applications. Lead acid and Nickel Cadmium, that are among the most common battery types have specific energy densities varying between 15 to 35 Wh kg^{-1} and 40 to 60 Wh kg^{-1} , respectively.

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Biographical Sketches

M. Sezai Dincer received his B.Sc. degree from ADMMA, Ankara, Turkey in 1975, M.Sc. degree from Middle East Technical University, Ankara, Turkey in 1979 and Ph.D. degree from University of Windsor, Ontario, Canada in 1985, all in Electrical Engineering. He worked at the University of Windsor as an instructor between 1984 and 1986. Until 1988, he worked at the Middle East Technical University as assistant professor. Currently he is a full time professor at the Department of Electrical and Electronics

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