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Batteries for Photovoltaic Applications
태양전지용 축전지

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ABSTRACT

Characteristics and properties of batteries applicable to the photovoltaic system are described in this paper. The use of a number of different types of batteries and designs depends on the many and varied requirements for battery power and the different environmental and electrical conditions under which they must operate.

Most of the batteries used in PV systems are lead/acid batteries, though nickel/cadmium batteries are used for small applications in locations with extreme climates or where high reliability is essential such as spacecraft. The vanadium redox battery has been acknowledged as a promising energy storage system for a wide range of applications.

1. Introduction

Battery is a device that converts the chemical energy contained in its active materials directly into electrical energy by means of an electrochemical oxidation-reduction(redox) reaction.

The storage battery in photovoltaic systems provides an energy levelling functions for the system. When more energy is produced by the array than that used by the loads (such as at midday on a sunny day), excess energy is stored in the battery. When less energy is produced by the array (such as on a cloudy day or at night), energy is extracted from the battery.

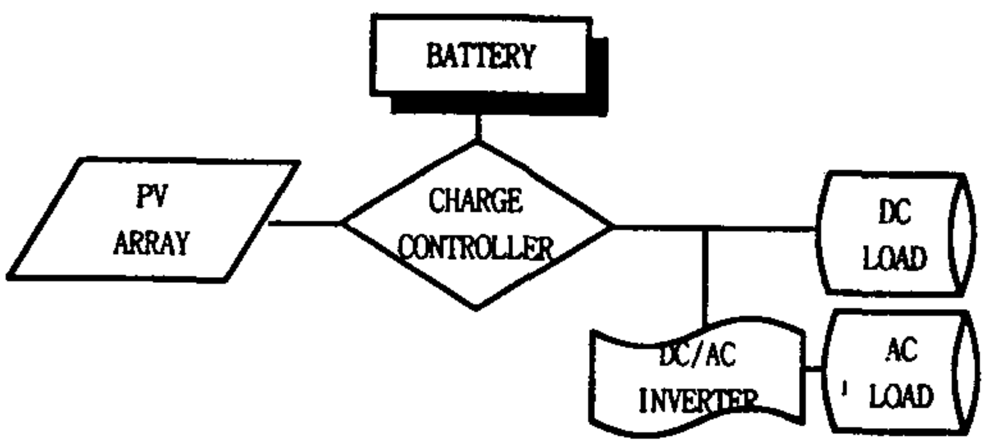

Fig. 1 Block diagram of a conventional PV system.

Figure 1 shows block diagram of typical photovoltaic system. In the PV system, operation conditions are quite different compared with conventional applications and the storage of energy in batteries is one of the cause of failures and loss of reliability of the system. The charging current is unpredictable and varies on a daily and seasonal basis.

In stand alone photovoltaic systems the battery costs can be 25% of the total installed systems costs. Developments in battery storage for PV will involve improving their reliability, increasing their lifetime and reducing their costs.[1] The various losses associated with the different components in the PV system are summarized in Table 1.[2]

Table 1. The various losses in a PV system.

Loss type	Range (%)	Average (%)
Module mismatch, dirt, dust	1.5 ~ 3	2
Wiring and control panel	0.3 ~ 1	0.5
Battery	5 ~ 15	10
Charge controller: poor efficiency high efficiency	 15 ~ 30 6 ~ 15	 20 <10
Maximum power tracker	6 ~ 10	7
Power conditioning unit	8 ~ 15	9
Load mismatch	7 ~ 9	8

The major losses occur in the controller, the power conditioning unit, the battery, and the mismatch of the load to the array. The losses of battery depend on the type of battery cells, the manufacturing process, and the state of charge. The operating voltage is mostly lower than the maximum output voltage of the PV array in the battery system directly connected with the PV array and this effect decrease the system efficiency(load mismatch). The PV system designer must carefully select the parameters of the array and the battery in order to match the load demand.

Batteries for photovoltaic power systems should meet the following features:

- long operational life time
- low self-discharge
- good reliability under cyclic conditions
- high charge storage efficiency
- low cost per capacity
- low maintenance costs
- endure a range of operating temperature
- safe in handling, operation and maintenance
- minimal environmental impact

The use of a number of different types of batteries and designs depends on the many requirements for battery power and the different environmental and electrical conditions under which they must operate.

In this paper, the battery principle and the various types of battery used for PV systems would be reviewed.

2. Battery principle

The most advantageous combinations of anode and cathode materials are those that will be lightest and give a high cell voltage and capacity. In practical system, the anode is selected with the following properties in mind: efficiency as a reducing agent, good conductivity, stability, ease of fabrication, and low cost. Metals are mainly used as the anode material. The cathode must be an efficient oxidizing agent, stable when in contact with the electrolyte, and have a useful working voltage. Most of the cathode materials are metallic oxides, but recently other cathodes have been used for advanced battery systems giving high voltages and capacity. The electrolyte must have good ionic conductivity but not be electrically conductive as this would cause internal short-circuiting. Other important characteristics are nonreactivity with the electrode materials, little change in properties with change in temperature, safe in handling, and low cost.

The standard potential of a cell can be calculated from the standard electrode potentials as follows (the oxidation potential is the negative value of the reduction potential):

Anode(oxidation potential)
+ cathode(reduction potential)
= standard cell potential

The theoretical voltage is a function of the anode and the cathode materials, the composition of the electrolyte, and the temperature.

From thermodynamics the voltage can be related to the nature of a current-producing reaction.

$$E = -\frac{\Delta G}{nF} \qquad (1)$$

ΔG is change of free energy of the reaction, n is the number of electrons(or chemical equivalents) taking part in the reaction and F is the Faraday (96,500 C/mol).

Battery capacity is the total number of

ampere-hours or watt-hours that can be withdrawn from a fully charged cell or battery under specified conditions of discharge without the battery voltage falling below a prescribed value. The battery capacity is measured in kilowatt-hours (kWh) or ampere-hours(Ah), at a constant discharge rate.

Watt-hour(Wh)

= voltage(V) X ampere-hour(Ah)

The rate of discharge affects capacity. PV system typically has a 300 hour discharge rate which, for lead-acid batteries, gives them approximately double the capacity specified at a 10 hour rate. Battery capacity is affected by temperature, falling by about 1% per degree below about 20℃. At the other extreme however, high temperatures accelerate aging, self-discharge and electrolyte usage.

There is a considerable importance placed on the efficiency of batteries, due to the relatively high cost of the photovoltaic array. Battery efficiency can be characterised as follows:

- Coulombic, or charge efficiency - usually measured at a constant discharge rate, referring to the amount of charge able to be retrieved from the battery, relative to the amount put in during charging. Self discharge will affect coulombic efficiency.
- Voltage efficiency- also measured at a constant discharge rate and reflecting the fact that charge is retrieved from the battery at a lower voltage than was necessary to put the charge into the battery.
- Energy efficiency - the product of the coulombic and the voltage efficiencies.

Depth of Discharge (DOD) is the ratio of the quantity of electricity(usually in ampere-hours) removed from a secondary cell or battery on discharge to its rated capacity. Shallow cycling batteries should not be discharged more than 25% of rated capacity, while deep cycling batteries can be discharged up to 80%.[3] Since battery life is a function of the average state of charge of the battery, a compromise must be made when designing a system between cycling depth and size of the battery bank.

State-of-Charge (SOC) is the available capacity in a cell or battery expressed as a percentage of rated capacity. Charging and discharging characteristics are important factors to determine the useful life of batteries. Battery life is greatly affected by the depth of discharge, rate of discharge, rate of charge, maximum state of charge and temperature.

3. PV stand-alone system

Stand-alone systems rely on PV power only and the batteries must be large enough to store the energy produced during the day for use at night. The battery is one of the most vital components in a stand alone photovoltaic system. Battery maintenance can be a major limitation for

PV stand-alone systems. In remote locations they may also be required to store energy produced on good days for use during periods of poor weather. The maxium power generated by photovoltaic (PV) arrays is not fully used due to the energy losses caused by the mismatch between the array and the load or battery, the loss in the batteries and the loss due to the PV array disconnect. The main reasons for the mismatch loss are also related to the battery. [4]

3.1 Lead/acid batteries

The lead-acid battery uses lead dioxide as the positive electrode and metallic lead as the negative electrode. Lead-acid batteries are the most commonly used in present stand-alone power systems. The lead-acid batteries commonly used in the car are not well suited for the deep discharge cycles experienced by batteries in PV systems.

As the worldwide consumption of batteries is at such a high level, environmental aspects are commanding increased attention. Modern recycling techniques of lead/acid batteries have been practised for economic and environmental reasons.[5]

3.1.1 Flooded lead/acid battery

The most attractive lead acid battery for use in most PV system is a flooded tubular plate design which generally give the best performance in terms pf sevice life. The tubular plate is composed with low antimony plates which give a low rate of self-discharge. Selenium is used because of its high grain-refining effect which helps to avoid the embrittlement of grids that is pervalent with low antimony alloys. Open, or flooded electrolyte, batteries contain an excess of electrolyte and gassing is used to reduce electrolyte stratification. The charging regime need not be stringent. However, electrolyte must be replenished frequently and the battery housing must be

$$Pb + PbO_2 + 2H_2SO_4 \xrightarrow{\text{discharge}} 2PbSO_4 + 2H_2O \quad (2)$$

well ventilated to prevent the build-up of hydrogen gas. In order to incorporate totally maintenace free characteristics gas-recombination catalytic vent plugs are manufactured. These plugs use a platinum catalyst on a alumina/silica carrier to recombine the hydrogen and oxygen gases that are evolved during overcharging. Water formed by the reaction returns to the cell.[6]

3.1.2 Sealed lead/acid battery

The sealed lead acid battery is designed mainly to avoid problems of spillage and the need for frequent addition of water.

Hydrogen and oxygen are produced from self discharge or from the electrolysis of water when the acid concentration is high or the cell voltage becomes greater than the gassing voltage(2.39eV at 25℃). In a sealed battery pressure release valve maintains an internal pressure of about 4×10^5 Pa, which helps hydrogen and oxygen recombine to water by keeping the gases within the cell. Sealed type has following benefits: elimination of the need for frequent addition, flexibility in orientation and installation, reduction in weight, leak-proof construction with total elimination of acid mist and spillage. However, they are typically less resistant to extremes of temperature than conventional flooded batteries and considerably more expensive (twice the cost of flooded lead/acid). Sealed batteries are valve-regulated to allow for evolution of excess hydrogen gas. However, catalytic converters are used to convert as much evolved hydrogen and oxygen back to water as possible. They are called "sealed" because electrolyte cannot be added. They require stringent charging controls because overdischarge results in acid starvation and the deposition of lead sulfate within the separators.

3.2 Redox flow battery (RFB)

In order to maintain energy capacity and long battery life in lead/acid battery, extra energy must be supplied periodically to the battery to de-statify the electrolyte and to equalise the cell voltages. This process of boost charging causes hydrogen evolution and water loss from the battery. A new type of electro-chemical storage was developed to overcome the constraints imposed by lead/acid technology.

In redox flow battery (RFB), the reactant solutions themselves serve as the electrolyte and electrical energy is stored by the oxidization of the positive electrolyte and the reduction of the negative electrolyte. The RFB is composed of inert electrode, the positive and the negative electrolyte, pumps, and so on, as shown in Fig. 2. An ion selective membrane is used to control ion transfer between separate solutions of the active materials as they are pumped through the battery. The electrochemical reactor unit is decoupled from the storage unit, yielding advantages in ease of design and in costs of both operation and maintenance of the system. Another advantage is the fact that both the

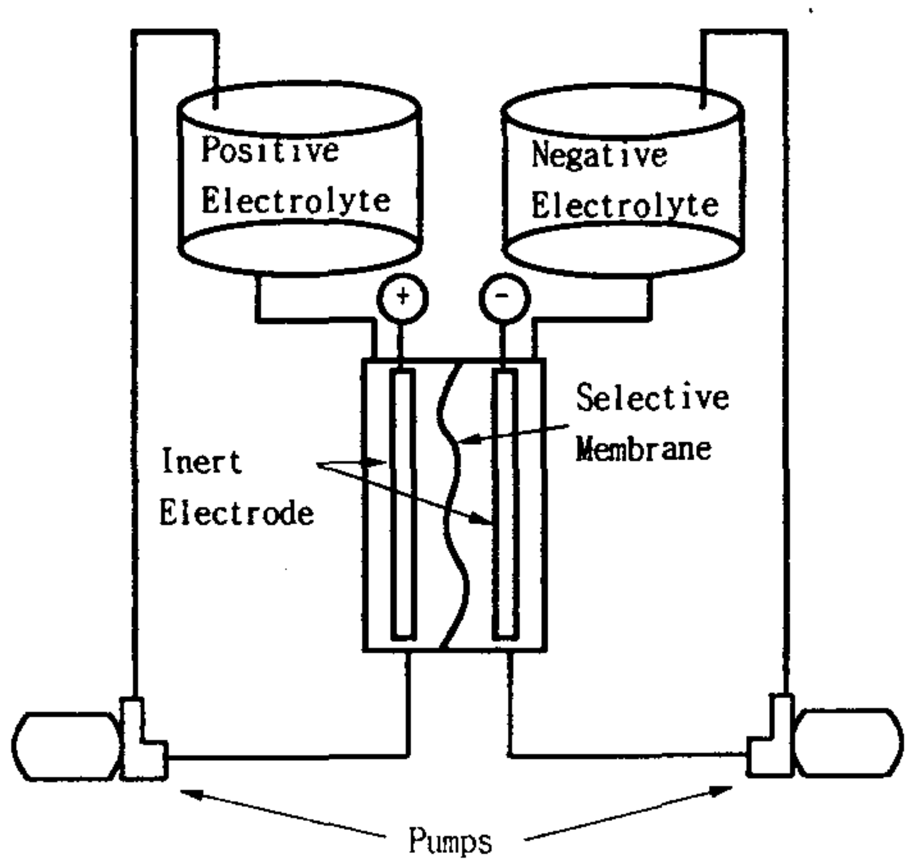

Fig.2 Schematic view of redox flow battery.

reactants and reaction products are soluble and thus possess no physical form to be maintained. As a result, there are no inherent life-limiting factors associated with electrode morphology changes. The absence of highly reactive or toxic substances generally minimizes safety and environmental problems.

The daily and annual simulation results show that charging efficiency, capacity and cycle life of the RFB is larger than the lead acid battery.[7] A coulombic efficiency of 98%, voltage efficiency of 94%, and an overall energy efficiency of 91.8% were obtained at a constant charging and discharging current density of 14.5mA/cm^2 for a test vanadium-redox flow cell.[8] The 2~3% energy loss of the total battery energy is calculated when the vanadium battery operates at full power. The strategy to minimise this energy loss and improve system efficiency is to turn the pumps off during periods of low charge or discharge rate.

The Thai Sypsum Products Co., Ltd., (TGP) is in the process of commercialising the 4 kW vanadium battery with the first application of the technology being a 300 house installation in Bangkok.[9]

They are mechanically complex because they need pump to circulate the electrolyte.

4. Batteries used for solar cars

One of the critical components of solar powered cars is the battery. It must allow deep cycling, yet have a longer life than present car batteries. The charge capacity/weight ratio is critically important though self discharge rates are not important.

4.1 Silver/zinc battery

The leading car in 1990 Solar Challenge used mostly silver/zinc. Of the top 15, twelve had silver/zinc, two had lead/acid, and one had nickel/zinc. Although silver/zinc is far more expensive than the other types of batteries, it has a much higher energy density. There are several properties of silver/zinc batteries that can cause serious problems such as limited recharge capability and difficulty in determining the state of charge. They are considered a "one-race" battery with their short life time.

5. Aerospace applications of batteries

The first space solar array was carried aloft on Vanguard I on March 17,1958. NASA(National Aeronautics and Space Administration) has developed battery technology to meet the demanding requirements for aerospace applications. Space power systems depend on orbit location (LEO;low Earth orbit, HEO;medium Earth orbit, GEO;geostationary Earth orbit) and power requirements. Battery charge and discharge cycles differ extensively, depending on the sunlight-to-eclipse ratio of the orbit. The storage subsystem must be designed to provide all the satellite power requirements during eclipse and to be fully recharged during the sunlight portion of the orbit. Also frequent eclipse imposes severe temperature cycles from -150℃~60℃ for low orbits. Table 2 lists charging time, discharging time and typical battery duty cycles with each aerospace application(orbit)[10.]

Table 2. Typical aerospace battery duty cycler.

Aerospace application (orbit)	Minimum charge time	Maximum discharge time	Cycles per year
Low Earth	60 min	35 min	6000
Geostationary	22.7hour	1.3 our	90

At present, nickel/cadmium batteries are used most often for space applications. The Secondary Battery Technology Task in NASA's Lewis Research Center (LeRC) includes both nickel/cadmium and nickel/hydrogen battery activities. NASA has used nickel/cadmium batteries for over 160 satellites to low Earth orbit, geostationary orbit, and the nearby planets. At 20% DOD, commonly used for space nickel/cadmium batteries to guarantee a 5 year life in a low earth orbit, the specific power ranges from 4 to 8 W/kg.[11]
In a geostationary orbit the storage subsystem mass may be lower because so few battery cycles are required and the charging may take place over a 23 hour period.

5.1 Nickel/cadmium

Nickel/cadmium batteries are commonly used as rechargeable batteries for household appliances and can be suitable for stand-alone PV systems. "Pocket plate" nickel/cadmium batteries can be used in PV system because they have additives in their plates to prolong their life and to minimise the memory effect. The main advantage of nickel/cadmium in PV applications is its ability to withstand harsh operating environments in particular overcharging and prolonged deep discharge. In addition, they have excellent low temperature performance and can be frozen without damage to the cells because the alkaline electrolyte of the nickel/cadmium does not become diluted during the discharge process. They have a number of advantages over lead/acid battery such as: low internal resistances, higher charging rate, uniform voltage during discharge, longer life time, low maintenance requirements and low discharge rate.

However, they also have a number of disadventages. They are typically two to three times more expensive, have lower charge storage efficiencies(75%), can require full discharge to prevent memory development and have a much lower capacity increase due to low discharge rates

5.2 Nickel/hydrogen and nickel/metal hydride

The characteristics of the system which make it particularly attractive for aerospace applications are high reliability, no maintenance, and extremely long life. In nickel/hydrogen and nickel/metal hydride batteries, the toxic cadmium in nickel/cadmium batteries is replaced by hydrogen. This battery is a combining battery and fuel cell, in which the electrodes are hydrogen and NiO(OH). During charge, hydrogen gas is generated from water, and $Ni(OH)^2$ is reduced to NiO(OH). Hydrogen can be stored under pressure within the cell, or it can be stored as metal hydride to minimize the risk of hydrogen explosions. They have cycle lives greater than any other battery system, almost equalling fuel cells. The Orbit Replacement Unit(ORU) in which 38 individual pressure vessel (IPV) Ni-H2 battery cells showed less than 0.020 volts of cell voltage throughout the 3,000 cycles12.Individual pressure vessel (IPV) nickel/hydrogen technology was advanced at NASA Lewis for geosynchronous orbit (GEO) applications since not many cycles are required over the life of the battery system. There are 20 communication satellites in GEO using IPV nickel/hydrogen battereis.[13]

6. New batteries for PV

New environmental regulations, in

Table 3. Characteristics of batteries of different types used for PV

Battery type	Energy Density Wh/kg Wh/ℓ	Power density (50%DOD) W/kg	Cycle life (60~80%DOD) cycle	Energy efficiency %	Self discharge rate %
Lead/ Acid	40~45 ~100	98~128	800~1000	67~80	0.1~0.2 /day
Nickel/ Cadmium	~53 ~140	~160	>500 (100% DOD)	~80	10~15 /month
Nickel/ Zinc	~74 ~130	100~130	220~240 (60% DOD)	75~85	0.5~1.5 /day
Nickel/ Iron	45~60 -	94	800~1100	<65	-
Nickel/ Metal hydride	50~70 160~200	-	1000~5000	-	30~40 /month
Zinc/ Bromine	60~80 80~90	80~100	300~750	62~79	7~10 /week
Sodium/ Sulfur	70~100 70~80	80~100	600~1000	75~90	100 /week
Litium/ Iron sulfide	80~110 -	80~130	~300	-	-

Table 4. Advantages and disadvantages of different batteries used for PV systems.

Battery type	Merit	Demerit
Lead/ Acid	High power output capability Possible to make sealed type High reliability Comparative low cost	Low energy density Low resistance to overcharge and overdischarge
Nickel/ Cadmium	High resistance to overcharge and overdischarge High reliability Possible to make sealed type High energy and power density Long life	High cost of Ni and Cd Cd is pollutant Difficult to charge at a higher temperature Memory effect
Nickel/ Zinc	High energy density High power output capability Possible to make sealed type	Short life High cost of nickel
Silver/ Zinc	Highest energy density High discharge rate Low self discharge	High cost Low cycle life Decreased performances at low temperature
Nickel/ Iron	High resistance to overcharge and overdischarge Long life High energy and power density Hermetically sealed	Short life High cost of nickel
Nickel/ Metal hydride	High energy and power density Hermetically sealed High resisstance to owercharge and overdischarge	High self discharge rate at a high temperature High initial cost
Zinc/ Bromine	High energy density Comparatively low material cost Sealed type	Short life Troublesome maintenance Bromine is poisonous
Sodium/ Sulfur	High energy density High power output capability Hermetically sealed Easy to measure residual capacity	Opeation at a high temperature Low resistance to overcharge and overdischarge Na and S are designated as dangerous objects
Litium/ Iron sulfide	High energy density High power output capability Hermetically sealed	Operation at a high temperature Short life High initial cost Li is desingnated as dangerous object

particular on cadmium and lead, has stimulated developments in alternative batteries to lead/acid and nickel/cadmium.

The properties of new batteris applicable to PV system are summarized in Table 3 and table 4.

7. Conclusion

Characteristics and properties of batteries applicable to the photovoltaic system with performance requirement for the application are summarized. The batteries for PV must be relatively maintenance free, exhibit low self-discharge and demonstrate relatively long charge/discharge cycle life. However in practice, when selecting an optimum battery one should consider many factors depending on the applications.

Lead/acid battery is used extensively in stand-alone PV system. Nickel/cadmium batteries are being replaced by the Ni-H2 Individual Pressure Vessel (IPV) batteries for space applications. The vanadium redox battery can improve energy storage system for PV applications by increasing energy efficiency and reliability. Batteries such as nickel/iron, nickel/zinc, zinc/bromine, sodium/sulfur and litium/iron sulfide are under development for PV.

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