Marcelo Godoy Simões

Lecture #11

Energy Storage

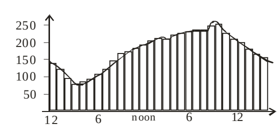
- **Energy storage technologies are classified according to the energy, time and transient response required for their operation**
- **It is convenient to define storage capacity in terms of the time that the nominal energy capacity can cover the load at rated power.**
- **Storage capacity can be then categorized in terms of:**
  - energy density requirements or in terms of power density requirements

Energy Storage Enhancements

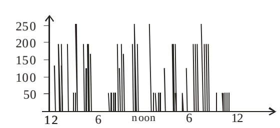
- **It stabilizes and permits DG to run at a constant and stable output, despite load fluctuations and required maintenance services.**
- **It provides energy to ride through instantaneous lacks of primary energy (such as those of sun, wind, and hydropower sources).**
- **It permits DG to seamlessly operate as a dispatchable unit.**
- **Energy storage may be designed to rapidly damp peak surges in electricity demand, counter momentary power disturbances, provide a few seconds of ride-through while backup generators start in response to a power failure, or reserve energy for future demand.**

Energy Storage Enhancements – Cont.

- **Residential Load**
  - Area average



  - One household

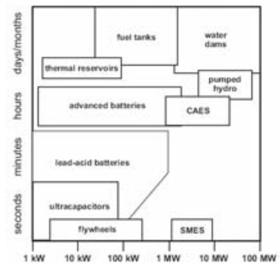


Storage Objectives Determine Storage Features

Storage Capacity	Energy Storage Features
Transient (microseconds)	• Compensates voltage sags • Rides through disturbances (backup systems) • Regenerates electrical motors • Improves harmonic distortion and power quality
Very short term (cycles of the grid frequency)	• Covers load during start-up and synchronization of backup generators • Compensates transient response of renewable-based electronic converters • Increases system reliability during fault management • Keeps computer and telecommunication systems alive for safe electronic data backup
Short term (minutes)	• Covers load during short-term load peaks • Smoothes renewable energy deficits for online capture of wind or solar power • Decreases need of start-up backup generator • Improves maintenance needs of fossil fuel-based generators • Allows ride-through of critical medical, safety, and financial procedures
Medium term (a few hours)	• Stores renewable energy surplus to be used at a later time • Compensates load-leveling policies • Allows stored energy to be negotiated on net-metering basis • Integrates surplus energy with thermal systems
Long term (several hours to a couple of days)	• Stores renewable energy for compensation of weather-based changes • Provides reduction in fuel consumption and decreases waste of renewable energy • Possibly eliminates fossil fuel-based generator backup • Requires civil constructions for hydro and air systems • Produces hydrogen from renewable sources
Planning (weeks to months)	• Includes large power storage systems, such as pumped hydro and compressed air systems • Uses fossil fuel storage to offset economic fluctuations • Stores hydrogen from biomass or renewable-based systems

Mature and Emerging Storage Technologies

- **Applications include lead-acid batteries, advanced batteries, low-energy and high-energy flywheels, ultracapacitors, superconducting magnetic energy storage system (SMES), heating systems, pumped hydro, geothermal underground and compressed air energy storage (CAES).**



Cost Projection of Energy Storage Systems

System	Typical Size Range MW	$/kW	$/kWh
Lead-acid batteries Advanced batteries	0.5–100 0.5–50	100–200 200–400	150–300
Ultracapacitors	1–10	300	3,600
Flywheels	1–10	200–500	100–800
SMES	10–1,000	300–1,000	300–3,000
CAES	50–1,000	500–1,000	10–15
Pumped hydropower	100–1,000	600–1000	10–15

Energy Storage Performance Criteria

- **Capacity –** The SI unit of capacity for energy storage is the joule, but this is a very small unit. Usually, the watt-hour (i.e., the energy equivalent of working at a power of 1 W for 1 hour, or 3,600 joules) is used instead.
- **Specific Energy –** Specific energy is the electrical energy stored per mass, in units of Wh.kg-1. Specific energy is ordinarily used when the energy capacity of a battery needed in a certain system is known; it is then divided by the specific energy to give an approximation of battery mass.
- **Specific Power –** It is the amount of power obtained per kilogram of a storage system in W.kg-1. It is a very sensitive parameter because several storage systems cannot operate at this maximum power for long time, as they may have impact on lifetime or operate very inefficiently.

Energy Storage Performance Criteria – Cont.

- **Energy Density –** Energy density is a measure of energy stored per volume in Wh.m-3. It can be used to give an approximation of the energy storage volume for a given application.
- **Physical Efficiency –** Physical efficiency is how much power is stored in a given volume and mass. It is usually considered in batteries for transportation applications, in which industry may accept degradation in electrical efficiency in return for good physical efficiency.
- **Electrical Efficiency –** Electrical efficiency is an important parameter for DG applications. It is the percentage of power put into a unit that is available to be withdrawn. It is measured by the energy capable of being converted into work. A unit with 90% efficiency returns 9 kWh of energy for every 10 kWh put in its storage.

Energy Storage Performance Criteria – Cont.

- **Recharge Rate –** The recharge rate is the rate at which power can be pushed for storage. A storage system might take 10 hours to deplete but 14 hours to refill.
- **Specific gravity –** Specific gravity is a dimensionless unit defined as the ratio of density of a material to the density of water at a specified temperature.
- **Self-Discharge –** Self-discharge indicates how long batteries take to discharge when unused. This is usually due to current leakage and heat dissipation.

Energy Storage Performance Criteria – Cont.

- **Lifetime –** Lifetime is the service life of a unit, and it varies with technology and intensity of usage. Batteries are noted for having short lifetimes in applications in which they are repeatedly charged and discharged completely.
- **Capital Cost –** Capital cost is the initial cost for design, specification, civil works, and installation in dollars per kilowatt.
- **Operating Cost –** Operating costs are the costs in dollars per kilowatt-hour for periodic inspection, fuelling, maintenance, parts (bearings and seals) replacement, recalibration, etc.

Typical Battery Parameters

	Specific Energy $Wh.kg^{-1}$	Energy Density $Wh.L^{-1}$	Specific Power $W.kg^{-1}$	Nominal Cell Voltage
Lead-acid	30	75	250	2.0 V
Nickel cadmium	50	80	150	1.2 V
Nickel metal hydride	65	150	200	1.2 V
Zebra	100	150	150	High voltage, integrated stack
Lithium ion	90	150	300	3.6 V
Zinc-air	230	270	105	1.65 V

Lead Acid Battery

$$\underset{cathode}{Pb} + 2H_2SO_4 + \underset{anode}{PbO_2} \underset{charge}{\overset{discharge}{\rightleftarrows}} \underset{cathode}{PbSO_4} + 2H_2O + \underset{anode}{PbSO_4}$$

- **The basic building block of a lead-acid battery is a 2-V cell. The batteries are wired together in series to produce 12-, 24-, or 48-V strings.**
- **Battery bank voltage and current rating are determined by inverter input, the type of battery, and the energy storage required.**
- **The flooded lead-acid battery is used in automobiles, forklifts, and uninterruptible power supply systems. Flooded-cell batteries have two sets of lead plates that are coated with chemicals and immersed in a liquid electrolyte. As the battery is used, the water in the electrolyte evaporates and needs to be replenished with distilled water.**

Characteristics of Lead-Acid Batteries

Advantages	Limitations
•Inexpensive and simple to manufacture •Mature, reliable, and well-understood technology •When used correctly, durable and provides dependable service •Self-discharge is among the lowest of rechargeable battery systems •Low maintenance requirements, no memory, no electrolyte to fill on sealed version •Capable of high discharge rates	•Low energy density, poor weight-to-energy ratio limits use to stationary and wheeled applications •Cannot be stored in discharged condition, cell voltage should never drop below 2.10 V •Allows only a limited number of full discharge cycles, well suited for standby applications that require only occasional deep discharges •Lead content and acid electrolyte make environmentally unfriendly •Transportation restrictions on flooded lead acid, environmental concerns regarding spillage, thermal runaway can occur with improper charging

Typical Lead-Acid Battery Parameters

Specific energy	20–35 $Wh.kg^{-1}$
Energy density	50–90 $Wh.L^{-1}$
Specific power	About 250 $W.kg^{-1}$
Nominal cell voltage	2 V
Electrical efficiency	About 80%, depending on recharge rate and temperature
Recharge rate	About 8 hours (possible to quick recharge 90%)
Self-discharge	1%–2% per day
Lifetime	About 800 cycles, depending on the depth of cycle

LA Batteries for RE Systems

- **The batteries used to start automobiles are known as shallow-cycle batteries because they are designed to supply a large amount of current for a short time and stand mild overcharge without losing electrolyte. Unfortunately, they cannot tolerate being deeply discharged. If they are repeatedly discharged more than 20%, their lifetime will be affected. Lead-acid batteries for automotive use are not designed for deep discharge and should always be kept at maximum charge using constant voltage at 13.8 V (for six-element car batteries). These batteries are not a good choice for RE systems.**
- **Deep-cycle batteries are designed to be repeatedly discharged by as much as 80% of their capacity, so they are a good choice for DG systems. Although they are designed to withstand deep cycling, these batteries have a longer life if cycles are shallower.**

Home

Charge Controller

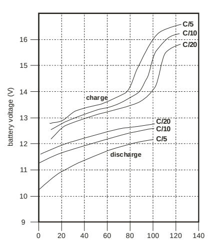
- A charge controller is essential to maintain batteries under optimized levels. It shuts down the load when a prescribed level of charge is reached and shuts down the connection to the main source (e.g., a photovoltaic array) when the battery is fully charged.
- When a charge controller manages a bank of batteries, it performs equalization of charge electronically.
- Equalization is a charge about 10% more than the normal float or trickle charge. This ensures that the cells are equally charged, and in flooded batteries, it ensures that the electrolyte is fully mixed by the gas bubbles.

Charge Controller – Cont.

- The optimum operating temperature for the lead-acid battery is 25 ºC.
- As a guideline, every 8 ºC (15 ºF) rise in temperature will cut the battery life in half.
- The capacity of a battery is referred to as C. Thus, if a load is connected to a battery such that it will discharge in n hours, the discharge rate is C/n.

Charge Controller – Cont.

- The terminal voltage depends on the charge or discharge rate and the state of charge for a typical lead-acid battery.



Charge Controller – Cont.

- It is extremely difficult to accurately measure the state of charge of a lead acid battery and predict the remaining capacity. In a battery, the rate at which input or output current is drawn affects the overall energy available from the battery. For example, a 100-Ah battery at a 20-hour rate means that, over 20 hours, 100 Ah are available (i.e., the user can expect to draw up to 5 A per hour for up to 20 hours). If a quick discharge is imposed, the effective Ah will be less.
- There are some commercial state-of-charge meters (called E-meters). They sample the rate of discharge every few minutes and recalculate the time remaining before the battery is discharged and also update and display a fuel gauge bar graph. The E-Meter also measures kilowatt-hours and historical battery information such as number of cycles, deepest discharge, and average depth of discharge. If an E-meter is not available, a voltage measurement of the open circuit voltage is a fair approximation of battery discharge.

Charge Controller – Cont.

- Lead-acid batteries are usually rated at a 5-hour discharge, or C/5. Some batteries are rated at a slow 20-hour discharge. Longer discharge times produce higher capacity readings.
- The lead-acid battery performs well on high load currents. Note that if the battery is charged at a C/5 rate, full charge will be reached at a terminal voltage of 16 V.
- However, if the battery is charged at C/20, then the battery will reach full charge at a terminal voltage of 14.1 V. When the charging current is zeroed, the terminal voltage will drop below 13 V.

Example of Characteristic Voltage Setpoints

- Quiescent (open-circuit) voltage: 12.6 V
- Unloading end voltage: 11.8 V
- Charge: 13.2–14.4 V
- Gassing voltage: 14.4 V
- Recommended floating voltage for charge preservation: 13.2 V.

- After full charge, the terminal voltage drops quickly to 13.2 V and then slowly to 12.6 V.

Maintenance

- A routine check-up of battery banks should be done every month to inspect the water level and corrosion on the terminals.
- At least two or three times a year, the state of charge should also be evaluated. As the battery discharges, more water is produced. A lower specific gravity is found in discharged batteries.
- State of charge, or the depth of discharge, can be determined by measuring the voltage or specific gravity of the acid with a hydrometer. These parameters will not support the battery condition; only a sustained load test can do that.

Maintenance – Cont.

- Voltage on a fully charged battery is typically 2.12–2.15 V per cell, or 12.7 V for a 12-V battery.
- At 50%, the reading will be 2.03 volts per cell, and at 0%, it will be 1.75 or less. Specific gravity will be about 1.265 for a fully charged cell and 1.13 or less for a totally discharged cell.
- The user should measure it with new batteries by fully charging them and leaving them to settle for a while and then taking a reference measurement.
- Hydrometer readings are not possible for sealed batteries, and only voltage readings are used for evaluation of the depth of discharge.
- Maintenance personnel should use only distilled water to avoid adding minerals that can reduce the batteries' effectiveness.
- Batteries should be brought to a full charge before adding water because the electrolyte expands as the state of charge increases .

Sizing Batteries

- The DC link where the battery charger is connected defines the string connection of battery cells.
- The DC link voltage usually fluctuates with the intermittence of the main source of energy (solar, wind, hydro, or other). Wind and hydro resources can be connected to the DC link with a rectifier or directly to the AC grid. If only a photovoltaic array is connected to the DC link, it will define the maximum DC link voltage.

Sizing Batteries – Cont.

- Batteries are specified with a nominal cell voltage equal to the open-circuit voltage (VCN) for a 100% state of charge, and that is the recommended float voltage of the cell.
- Let the cell voltage at the completion of discharge be denoted by final volts per cell (FVPC), which should be selected as high as possible, typically within 80%–90% of VCN :

$$FV_{pC} = 0.8V_{cn}$$

Sizing Batteries – Cont.

- Let VBAT represent the terminal voltage of the battery (consisting of a series string of NC cells) after discharge VBAT is equal to the minimum DC - link bus voltage, which is related to the minimum voltage at which an inverter connected to the DC link will operate. Then, the number of cells can be selected by the following ratio, taking the next higher integer value:

$$N_c = \frac{V_{bat}}{FV_{pC}}$$

Sizing Batteries – Cont.

- The decision of whether the battery should be sized for transient compensation or autonomous operation must be made at this point. When selecting a battery to compensate the main source (fuel cell or microturbine, for example) for changes in load demand, the typical transient response of the fuel cell or microturbine source must be empirically known and defined by the mathematical function g(t), which starts at zero and ends at the unity value at a time $T_{r,max}$.
- This function represents the source response to a step change in power, and either a ramp or an exponential function usually approximates it. Then, the maximum power drawn from the battery for compensating this transient is

$$P_{b,max}(t) = P_{fl}\,g(t)$$

where P_{fl} is the full load power (in kilowatts)

Sizing Batteries – Cont.

- The maximum energy storage required in the battery can be determined by:

$$E_{b,max} = \int_0^{T_{r,max}} P_{b,max}(t)dt$$

The integral can be approximated by:

$$E_{b,max} = K_1 P_{fl} T_{r,max}$$

where $K_1 = \int_0^{T_{r,max}} g(t)dt$

is evaluated to be 0.5 and 0.2 for ramp function and exponential function, respectively.

Sizing Batteries – Cont.

- The full load power (in kilowatts) P_{fl} can be obtained by:

$$P_{fl} = \frac{kVA_{fl} \cdot PF}{\eta} 10^5$$

where KVA_{fl} is the full-load kilovolt-amperes of the inverter, PF is the power factor of the load connected to the inverter, and η is inverter efficiency

Sizing Batteries – Cont.

- The battery energy is given by:

$$E_{b,max} = \frac{K_1 \cdot kVA_{fl} \cdot PF \cdot T_{r,max}}{\eta} 10^5$$

- The ampere-hour per cell, which is the C rate of the battery, is given by:

$$Ah = \frac{E_{b,max}}{N_c \cdot FVpC \cdot 3600} = \frac{K_1 \cdot kVA_{fl} \cdot PF \cdot T_{r,max}}{\eta \cdot N_c \cdot FVpC \cdot 3600} 10^5$$

Sizing Batteries – Cont.

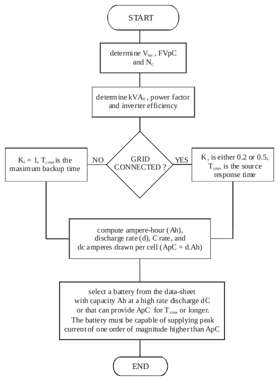
- Considering d as the multiplier that determines the discharge rate of the battery, then:

$$d = \frac{3600}{T_{r,max}}$$

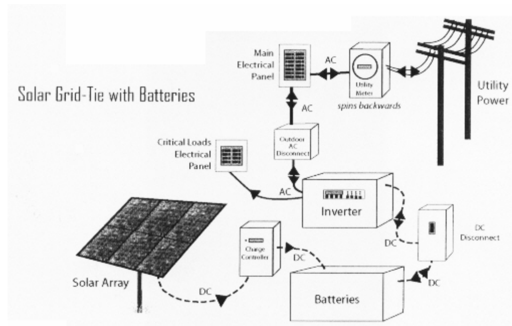
and the discharge rate of the battery is expressed as dC. The average current drawn from the battery during discharge is APC = dAh for a duration of Tr,max.

- The battery must be capable to supply peak current at least for one order of magnitude (i.e. about 10 X APC)

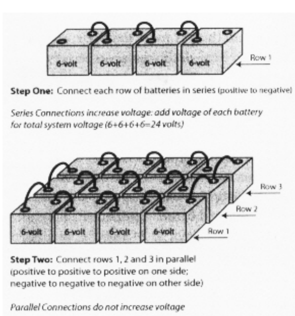
Flowchart for Sizing Batteries



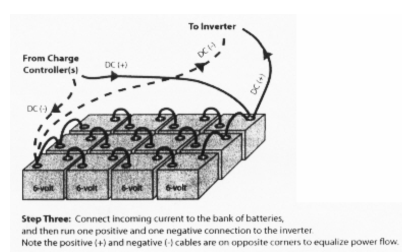
Battery System Integration



Basics of Wiring



Basics of Wiring - Cont.



Battery Bank Needs a Box

Notes #1

- Car batteries are not suitable for PV applications as they can not handle the deep discharges that can occur with PV systems.
- "RV" or "marine" batteries can handle a deeper discharge than car or starter batteries and can be used in a beginning system. They will last 2 to 3 years.
- Deep cycle batteries are available for golf carts, and include Industrial Chloride batteries. These batteries are the best choice for PV systems as they can be discharged 80%. The golf cart batteries will last 3-5 years. There are some larger capacity deep cycle batteries that will last 7-10 years. Industrial Chloride batteries will last 15-20 years.

Notes #2

- Nickel-cadmium batteries are costly but can last a very long time if they are not discharged excessively. A new type of nickel-cadmium battery, fiber-nickel-cadmium, has outstanding longevity at a 25% discharge rate. Nickel-cadmium (NiCad) batteries have different operating and maintenance characteristics than lead-acid batteries that must be considered. For example, it is difficult to measure the depth of discharge that is occurring with a NiCad battery since its output is constant right up to the last moments before being completely discharged. Check with the suppliers in the Resources section about the operation and maintenance characteristics of the NiCad batteries they offer.
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- For large systems, the best battery choices will be the "true" deep cycle types. Caution in using batteries must be observed along with recognition of their characteristics in response to temperature changes (lead-acid batteries operate less efficiently in cold temperatures) and ventilation requirements.