ENERGY STORAGE AND BATTERY MANAGEMENT SYSTEMS IN ELECTRIC VEHICLES – part 1

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LEARNING OUTCOMES

By mastering this subject, the students will be able to:

- Understand different storage media for electricity, especially regarding power density, delivered power, maintenance, cost, safety, and environmental impact.
- Understand basic principles and challenges with different charging principles.
- Understand operating principles of battery management systems in electric vehicles.

SUBJECT CONTENT

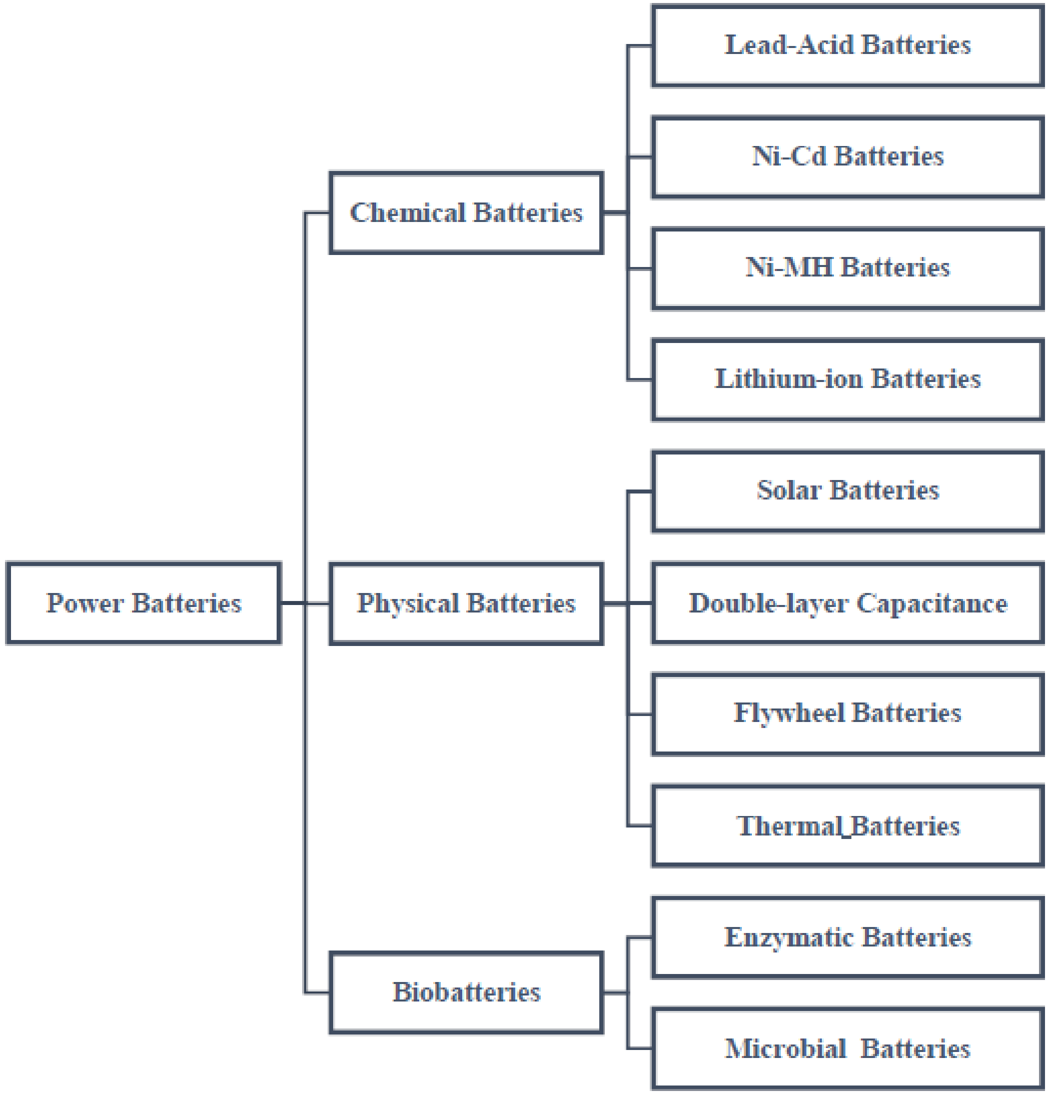
1. Introduction on energy storage systems in EV
2. Key technologies of storage media for electricity in EV
3. Basic parameters for evaluating energy storage systems
4. Power batteries as the main energy storage part in electric vehicles
5. Operation Principle and Types of Power Batteries
6. Performance Parameter of Power Battery
7. Battery Model
8. Key Technologies of Battery Management System (BMS)
9. Key parameter calculations with BMS
10. Monitoring and Estimating Battery parameters
11. State Estimation Methods
12. Optimized Charging Management
13. Thermal Management and Thermal Safety
14. Internal and external communication
15. Cloud Battery Management System

1. INTRODUCTION ON ENERGY STORAGE SYSTEMS IN EV

- Electric vehicle (EV) is the product of synthesis and integration of automobile engineering, electric drive, power electronics, automatic control systems, renewable energy and new materials.
- There are several different EV categories, including battery electric vehicle (BEV), hybrid electric vehicle (HEV) and fuel cell electric vehicle (FCEV).
- The structure of the BEV consists of the onboard energy storage system, powertrain system, chassis, vehicle body and auxiliary systems. The powertrain system includes motor, traction control system and transmission system.
    - The key technologies for BEV development include the powertrain system, steering system, suspension system, auxiliary systems, propulsion system and the vehicle control systems. Battery, motor and transmission system are the three most critical components of the BEV.

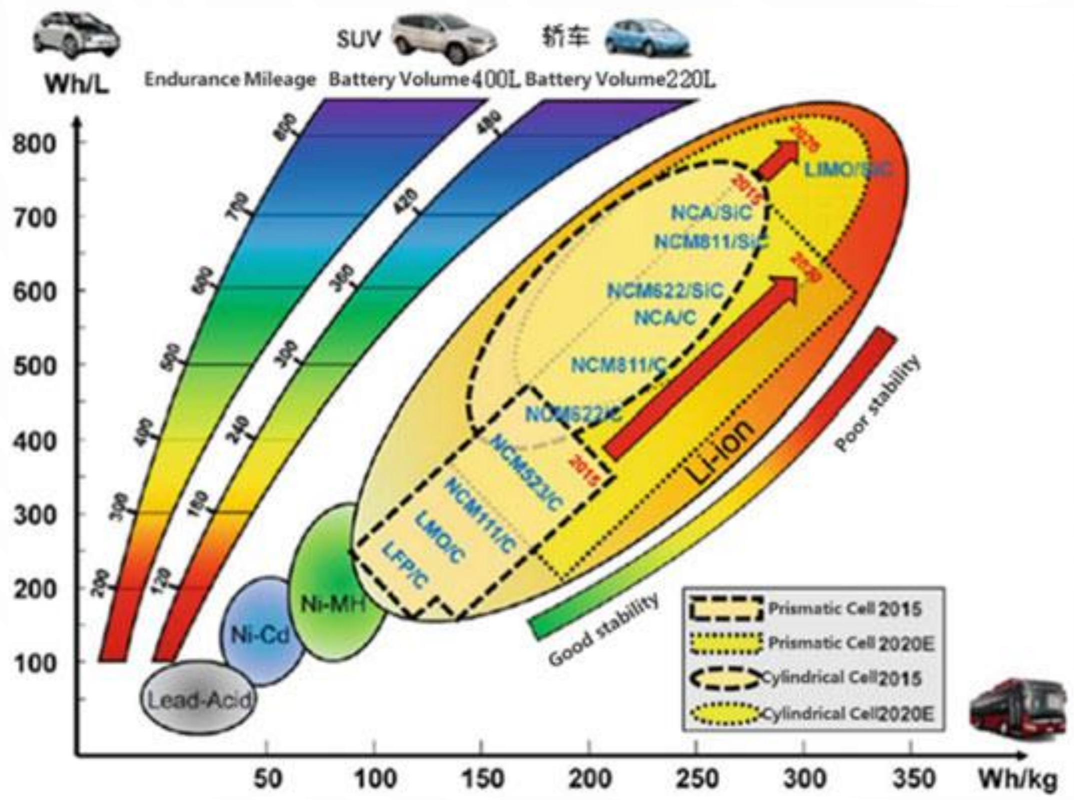
2. KEY TECHNOLOGIES OF STORAGE MEDIA FOR ELECTRICITY IN EV

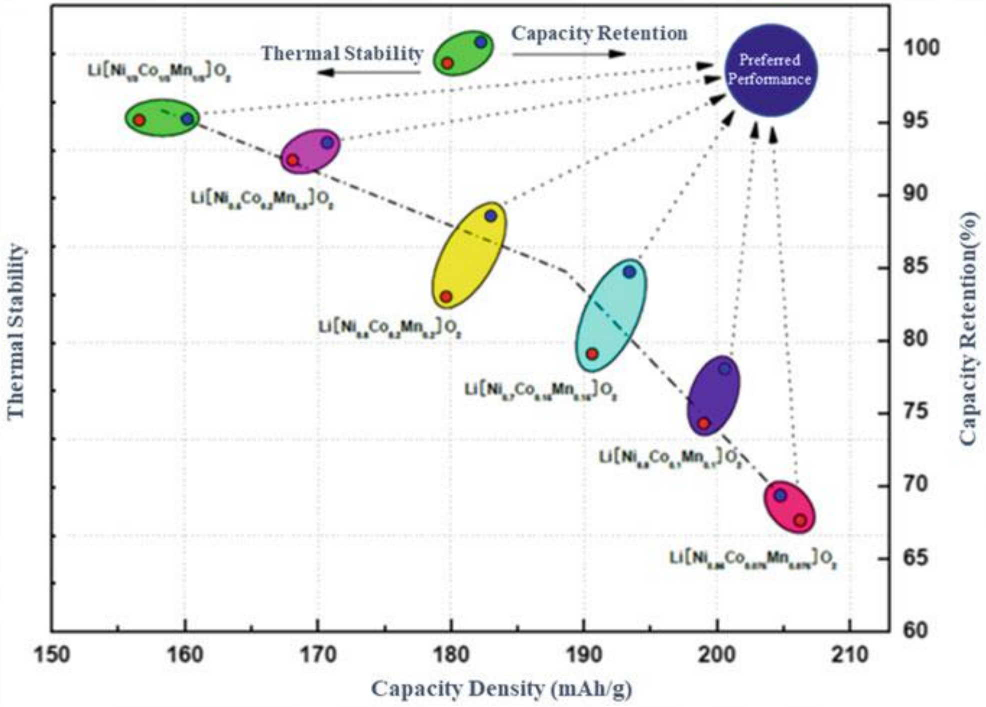
- Lead-acid, Ni–MH and lithium–ion batteries are common in electric vehicles. The energy density of lithium–ion batteries is the highest among the three types. Furthermore, the lithium–ion battery becomes the research focus due to its high power density, lowself-discharge rate, weak memory effect and environmentally friendly issue. lithium–ion batteries are applied in electric vehicles, hybrid electric vehicles and fuel cell vehicles.



2. KEY TECHNOLOGIES OF STORAGE MEDIA FOR ELECTRICITY IN EV

- Application status of vehicle power batteries





3. BASIC PARAMETERS FOR EVALUATING ENERGY STORAGE SYSTEMS

- Key Parameters
  - Storage Capacity (E, kWh or MWh) - Total amount of energy the system can store and deliver. Defines operating duration or autonomy.
  - Power Rating (P, kW or MW) - Maximum instantaneous power that can be absorbed or delivered. Determines how fast the system can charge/discharge.
  - Energy Density (Wh/L) and Specific Energy (Wh/kg) - Energy per volume/mass. Important for mobile applications (EVs, aviation).
  - Specific Power (W/kg) and Power Density (W/L) - Power delivered per unit mass/volume. Key for fast dynamic response applications (e.g., frequency regulation).
  - Round-trip Efficiency (%) - Ratio of discharged energy to charged energy. Typical values: Li-ion batteries 90–95%; Pumped hydro 70–85%; CAES 40–70%

3. BASIC PARAMETERS FOR EVALUATING ENERGY STORAGE SYSTEMS

- Key Parameters
  - Lifetime (Cycle Life & Calendar Life)
    - Cycle life: number of charge/discharge cycles until degradation.
    - Calendar life: total time system can operate regardless of cycles.
  - Response Time
    - Time required to begin delivering power.
    - Supercapacitors & flywheels: milliseconds
    - Batteries: seconds
    - Pumped hydro: minutes
  - Self-discharge / Standby Losses
    - Energy lost when the system is idle.
    - Supercapacitors and thermal storage: high
    - Batteries and PHS: relatively low

3. BASIC PARAMETERS FOR EVALUATING ENERGY STORAGE SYSTEMS

- Key Parameters
  - Safety and Reliability
    - Risks of fire, explosion, material degradation, or mechanical failure.
    - Li-ion requires BMS, while pumped hydro has high inherent safety.
  - Scalability and Modularity
    - How easily the system can be expanded or downsized.
    - Batteries are modular, while PHS and CAES depend on geography.
  - Cost ($/kWh for energy, $/kW for power)
    - Economic feasibility is critical.
    - Example:
      - Li-ion ~120–140 $/kWh (2024–2025)
      - Pumped hydro: lower cost per kWh but high upfront investment.

4. POWER BATTERIES AS THE MAIN ENERGY STORAGE PART IN ELECTRIC VEHICLES

- Most of the existing power battery system adopts three-level structure, that is, cell level, module level, system level

- First, multiple cells are combined into modules according to different series–parallel connection modes, and then a certain number of modules are combined into a battery system, the battery module includes a single cell, a fixed frame, an electrical connection, a temperature sensor, a voltage detection circuit, etc..

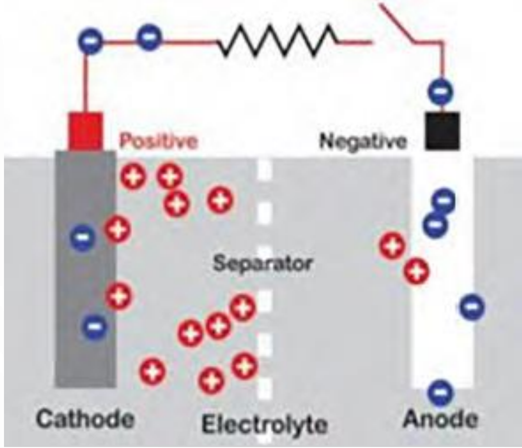
4. POWER BATTERIES AS THE MAIN ENERGY STORAGE PART IN ELECTRIC VEHICLES

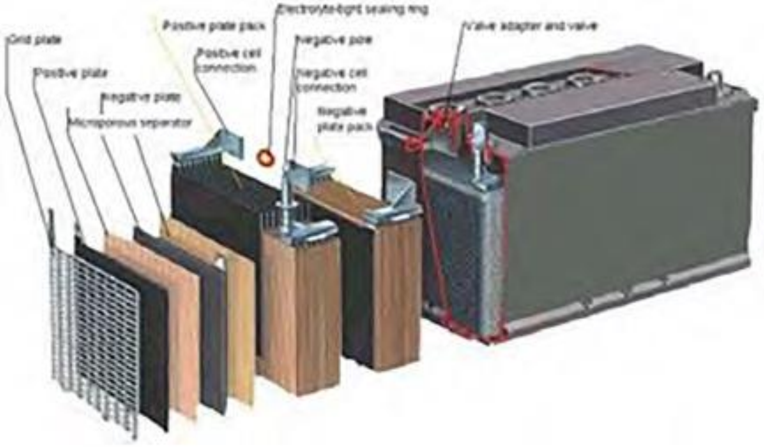
- Differentiating Characteristics of Different Battery Technologies

	Energy density (kW/kg)	Round Trip Efficiency (%)	Life Span (years)	Eco-friendliness
Li-ion	1st 150–250	1st 95	1st 10–15	1st Yes
NaS	2nd 125–150	2nd 75–85	2nd 10–15	2nd No
Flow	3rd 60–80	3rd 70–75	4th 5–10	4th No
Ni-Cd	4th 40–60	4th 60–80	3rd 10–15	3rd No
Lead Acid	5th 30–50	5th 60–70	5th 3–6	5th No

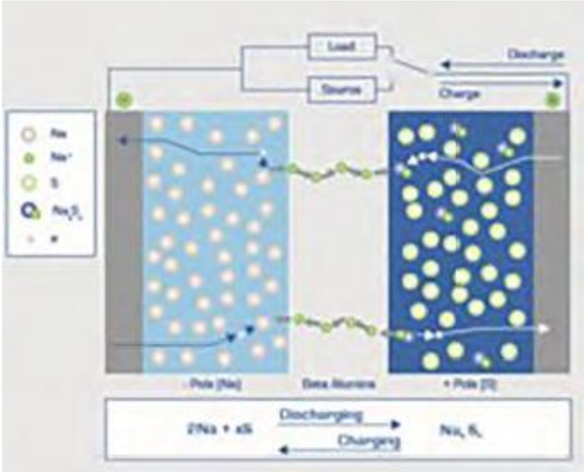
5. OPERATION PRINCIPLE AND TYPES OF POWER BATTERIES

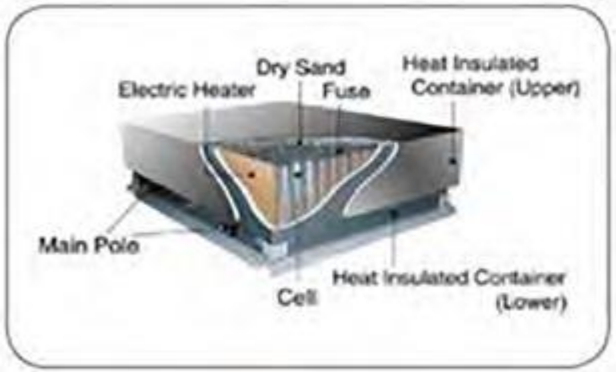
- Lead–Acid (PbA) Battery





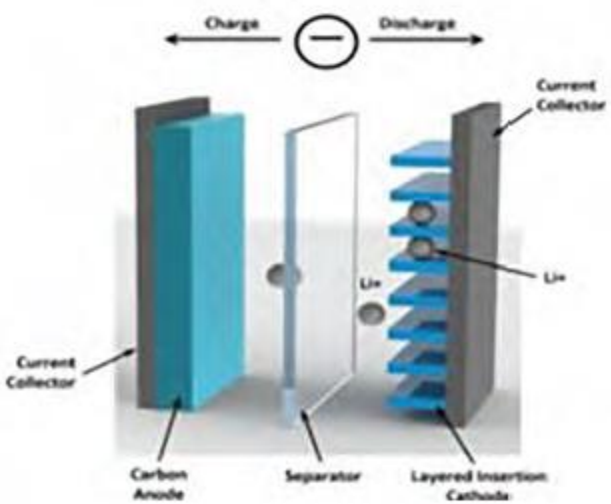
- Sodium–Sulfur (Na–S) Battery

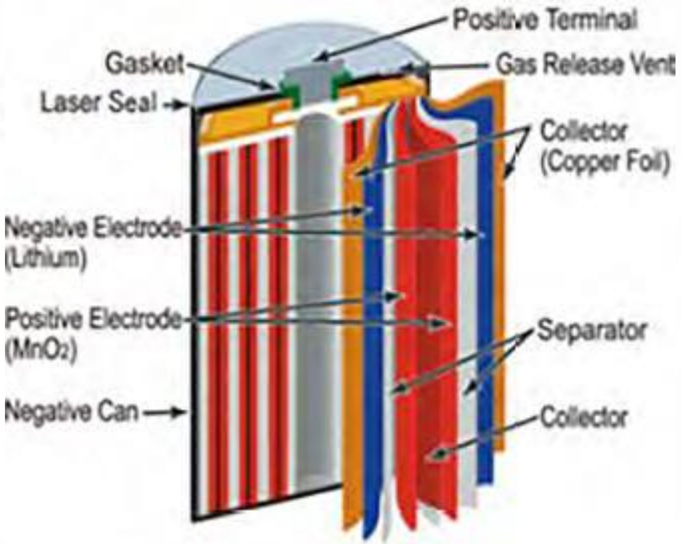




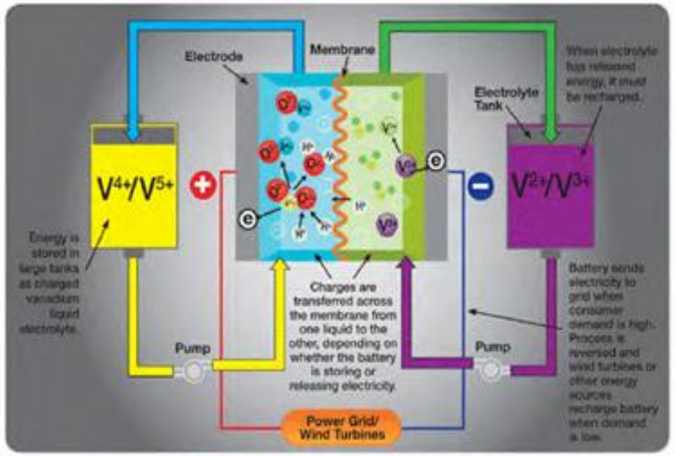
5. OPERATION PRINCIPLE AND TYPES OF POWER BATTERIES

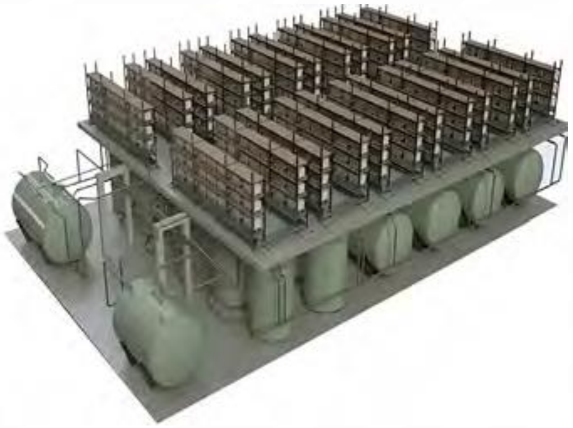
- Lithium-Ion Battery





- Redox Flow Battery (RFB)





6. PERFORMANCE PARAMETER OF POWER BATTERY

- Nominal Parameters
  - Storage Capacity Ah (C_T Theoretical and C_P Practical) - Total amount of charge the battery can store.

$$C_T = 26.8n\frac{m_0}{M} \qquad C_P = \int_{t_0}^{t_{cut}} i(t)\mathrm{d}t$$

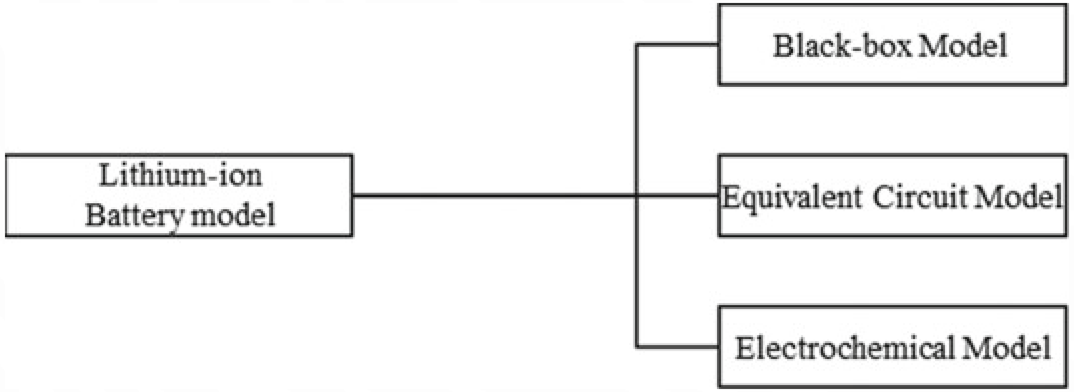
  - Nominal and Operating Voltage (V) - Depends on battery chemistry (e.g., 3.6–3.7 V for Li-ion cell). Determines pack design and compatibility with power electronics.
  - Internal resistance (Internal resistance is the resistance in current when batter is in use. It includes Ohmic resistance and polarization resistance)
  - Discharge/Charge Current
    - Discharge/charge rate is the rate between discharge/charge current and rated capacity. For example, the C rate for 2 A current in a 10 Ah cell is 0.2 C. Similarly, the C rate for 15 A current in a 10 Ah cell is 1.5 C.
    - Hour rate is the hours used in the full discharge of a cell at certain current. For example, hour rate for 10 A current in a cell with 50 Ah rated capacity is 5 h. The lower hour rate is, the higher the current is.

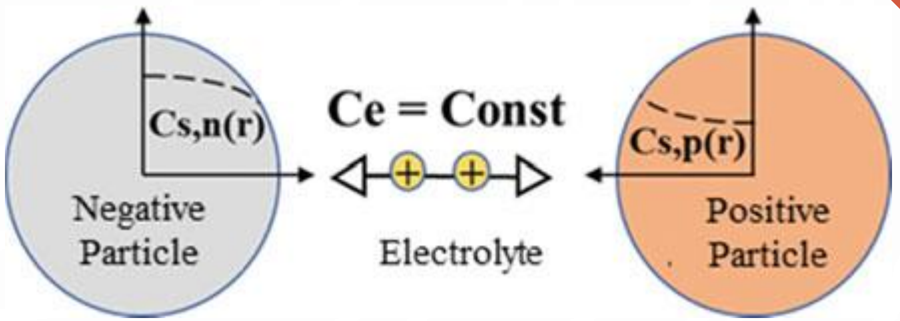
6. PERFORMANCE PARAMETER OF POWER BATTERY

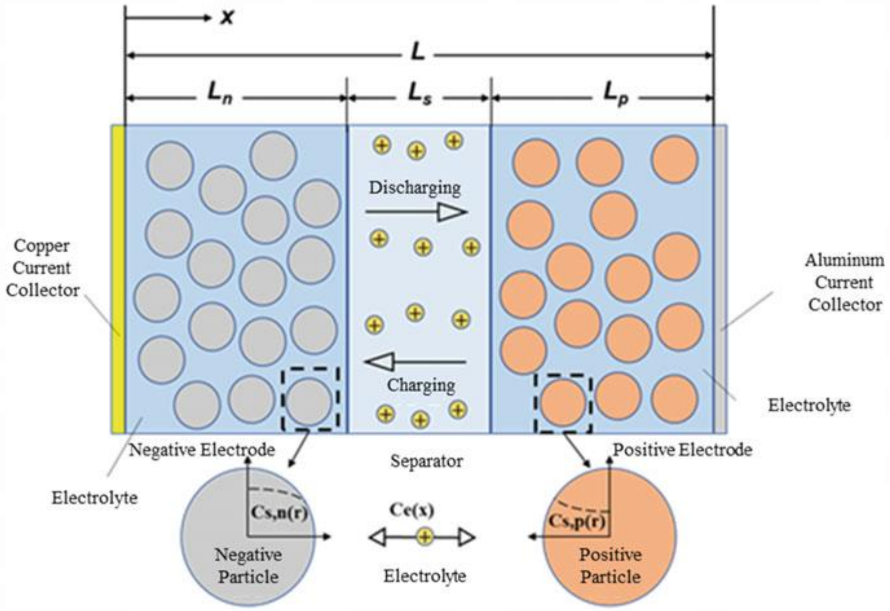
- Nominal Parameters
  - Specific Energy (Wh/kg) - Amount of energy stored per unit mass. Directly determines the driving range of the vehicle.
  - Specific Power (W/kg) - Power delivered per unit mass. Determines acceleration and regenerative braking capability.
  - Energy Density (Wh/L) - Energy per unit volume. Important for compact battery pack design.
- Other Parameters
  - Lifetime (Cycling lifetime is the maximum cycling number when the capacity reaches cutoff value under certain cycling condition. A cycle involves a charge and a discharge process. Cycling lifetime is affected by charge/discharge rate, depth of discharge and temperature etc.)
  - Self Discharge (Self discharge is the capacity loss from unexpected chemical reaction. Self discharge arises from thermodynamic instability of electrodes and their redox reactions)
  - Operating Temperature Range (°C) - Temperature range where the battery can function without major degradation. Typical: −20°C to 60°C, optimal 20–40°C.
  - Safety - Resistance to overcharge, short circuit, mechanical damage, high temperature. Critical for EV applications (ensured by BMS).

7. BATTERY MODEL

- Different types of battery models

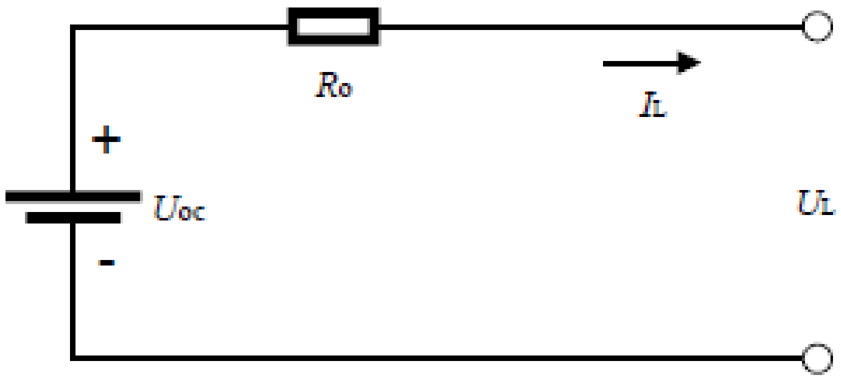






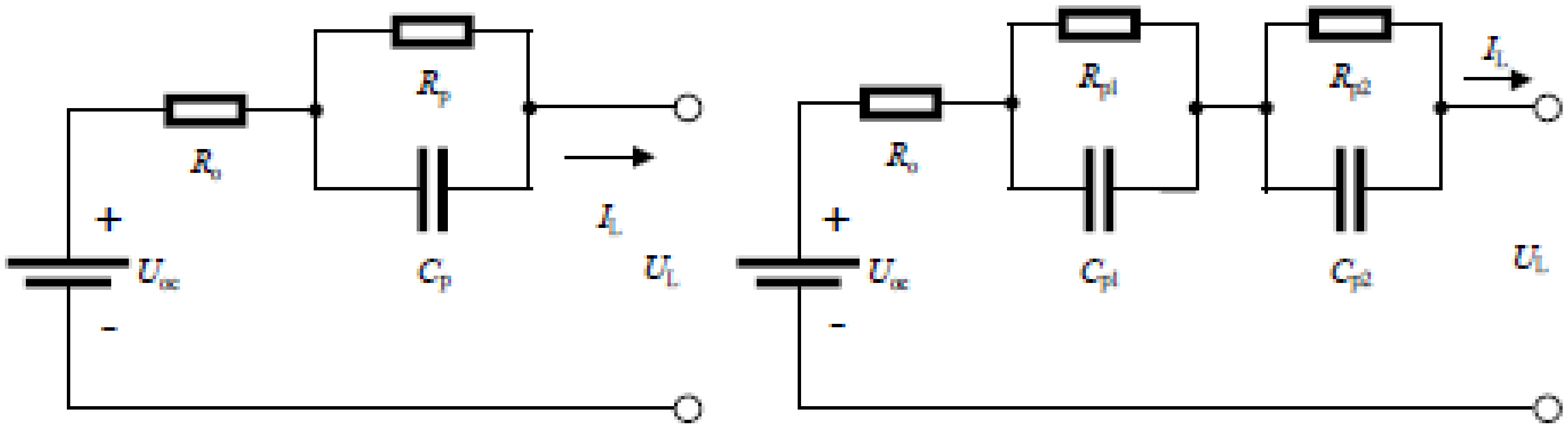
7. BATTERY MODEL

- Equivalent Circuit Model (ECM) – Resistance Model
  - The resistance model is the simplest ECM, which consists of an ideal voltage source Uoc and a series resistor Ro.
  - UL and IL represent the battery's terminal voltage and current, respectively.
  - Uoc and Ro are in turn the open-circuit voltage and the internal resistance of the battery.
  - Both Uoc and Ro depend on the battery SOC, SOH and temperature.



7. BATTERY MODEL

- Equivalent Circuit Model – The RC model of lithium-ion batteries uses RC networks in addition to the resistance model. This can improve the model accuracy under dynamic operating conditions. The model equations can be put in state-space form. The widely used RC models include the Thevenin model (with 1 RC network) and the DP model (with 2 RC networks)



(a) Thevenin model (b) DP model

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