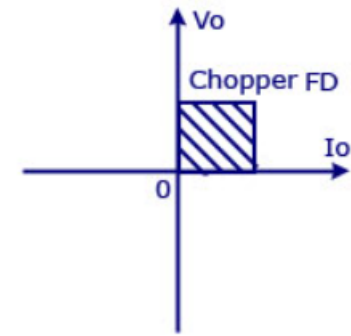
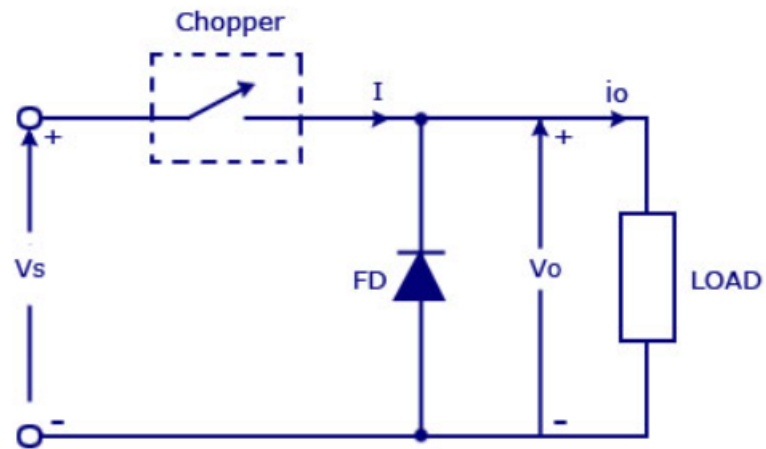


Electric Vehicles

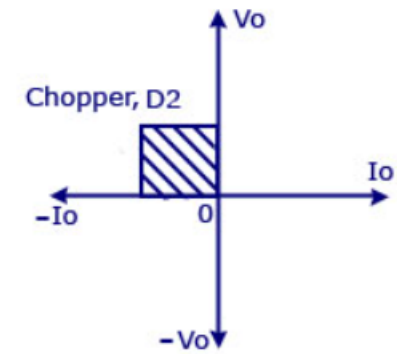
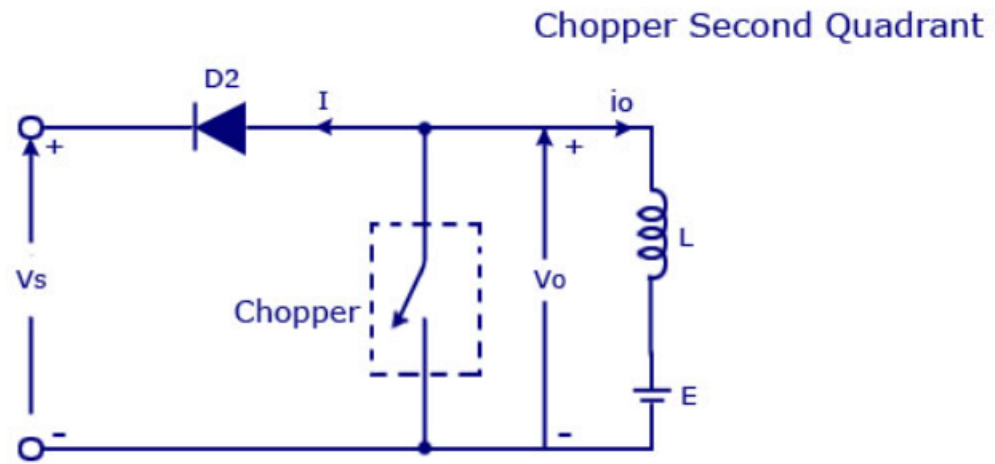
Pratyush Chakraborty

Type A chopper

Chopper First Quadrant

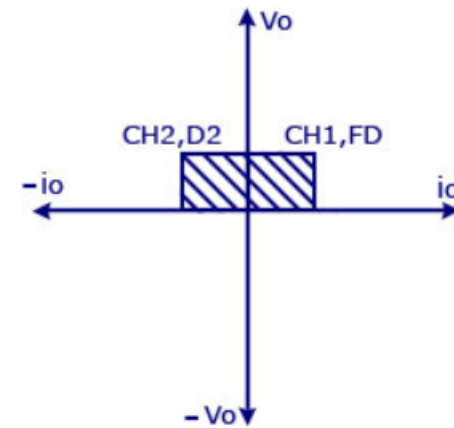
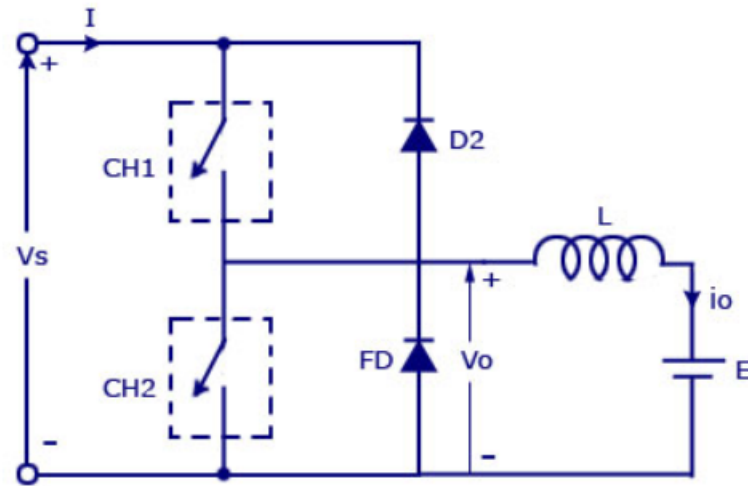


Type B chopper



Type C Chopper

Chopper Two Quadrant



Battery

- A battery consists of two or more electric cells joined together. The cells convert chemical energy to electrical energy.
- The cells consist of positive and negative electrodes joined by an electrolyte. It is the chemical reaction between the electrodes and the electrolyte which generates DC electricity.
- In the case of **secondary or rechargeable** batteries, the chemical reaction can be reversed by reversing the current and the battery returns to a charged state

Battery

- **State of health (SoH)** is a [figure of merit](#) of the condition of a [battery](#) (or a [cell](#), or a [battery pack](#)), compared to its ideal conditions. The unit of SoH is percent (100% = the battery's conditions match the battery's specifications).
- For example, when the capacity of a new battery is same as the nominal capacity as per the battery specification, it is said to be in optimal health (SoH = 100%). As the battery is further utilized in a device, its health as in its capacity and other useful parameters deteriorate till it reaches the end of life (SoH = ~70-80%).

DOD

- It's generally not recommended to discharge your battery entirely, as doing so could harm the system. To [protect against this](#), many manufacturers specify a maximum **depth of discharge, or DoD**, which measures the amount of electricity you can safely pull from the battery without damaging it, relative to its overall capacity.
- For example, if a 10 kWh battery has a DoD of 80%, you shouldn't use more than 8 kWh from the battery without recharging. A higher DoD means you can use more energy stored in your battery. Many modern lithium-ion batteries now advertise a DoD of 100%, meaning you can discharge all the stored electricity before recharging.

Battery

- ***Specific energy***

Specific energy is the amount of electrical energy stored for every kilogram of battery mass. It has units of $Wh.kg^{-1}$.

- ***Energy density***

Energy density is the amount of electrical energy stored per cubic metre of battery volume. It normally has units of $Wh.m^{-3}$.

- ***Specific power***

Specific power is the amount of power obtained per kilogram of battery. It is a highly variable and rather anomalous quantity, since the power given out by the battery depends far more upon the load connected to it than the battery itself.

Hybrid Energy Storage

- One method of achieving electrical energy storage with a high specific power is to use **ultracapacitors** (UC) in an hybrid energy storage setting. The use of UC's alone would not suffice, as these components display poor specific energy characteristics.
- The ideal solution is to use a hybrid energy storage method in a **parallel configuration**. This type of set up combines the high specific power of UC's with the higher specific energy of an electrochemical battery (B).
- This type of configuration is however more costly, due to the additional components and the additional complexity in controlling and managing both power sources.

Battery

- Electrochemical storage devices used in EV must fulfil certain requirements so that the EV can perform in a satisfactory manner.

The key requirements are as follows:

- High specific energy to ensure a satisfactory range
- High specific power so that drivers acceleration expectations can be met
- Long, maintenance-free lifetime
- Safe operation under a wide range of conditions
- End of life disposal has a minimum environmental impact
- High efficiency in charge and discharge cycles.

Battery

- Battery to be designed to provide Energy over a range as well as Peak Power
- Battery designed for certain **Energy (C) in kWh = $V * Ah / 1000$**

It comes from cell capacity defined in Ampere-hour (Ah)

Defined in terms of nominal voltage (V) and (current * hours) or Ah rating

- For long-life of rechargeable battery, it is never fully emptied or fully charged
- Useable energy each charge charge-discharge cycle is typically x% (may be 85%) of total capacity
- Also, **Battery Capacity reduces with each charge-discharge cycle**
- When battery capacity remaining is y% (typically 80%) of initial capacity, the range gets proportionately reduced: battery life for EV is OVER and it needs replacement
- So at end of its cycle life,
- usable capacity = $x * y * C = 0.8 * 0.85 C = 0.68C$

Battery

- Even when batteries have sufficient energy, rate at which Power can be taken out of battery (discharge rate) is limited
- Higher rate discharge impact the life-cycles of the battery
- Same is true about charging behavior: higher charging rate impacts life
- Higher rate charging-discharging also heats up the battery
- Battery has to be designed to have peak -power capability that the vehicle requires

Understanding Battery Parameters

- State of Charge (SoC) of battery is a measure of percentage of battery charged
- SoC of 0% means discharged battery; SoC of 100% is fully charged battery (having 15 kWh energy)
- Output Voltage of a Battery-pack varies with its SoC
- For a 48V Li-Ion battery, voltage varies from 43 to 56V depending upon the State of Charge (SoC)
- 43V when SoC is near zero and 56V when SoC is near 100%

Charging and Discharging at C-rate of Battery

- For a 15-kWh battery
- 1C charge / discharge rate means pumping in or taking out power at 15kW
can charge or drain the battery fully (SoC 0% and 100%) in 1 hour
- 2C rate implies push-in / pull-out power at twice the battery capacity rate, that is at 30kW battery will charge/discharge in 30 minutes
- 4C Rate: 60 kW charge / discharge rate -fully in 15 minutes
- 0.1C Rate: 1.5 kW or charge / discharge in 10 hours

Defining EV Battery Life

Consider a battery with a capacity of C to start with; Over time the capacity decreases due to

- Aging or time: Calendar life (typically 1% to 2% of capacity loss per year)
- Charge-discharge cycles: as batteries are charged / discharged, battery capacity decreases

Battery Life

- When the capacity becomes 80%(or 70%) of C , it may be termed as End of Life of battery implying the battery will no longer give range required by EV and therefore needs to be replaced
- For 15kWh battery: End of life capacity is 12kWh (80%) or 10.5 kWh (70%)
- these batteries can no longer be used in EV's as the range decreases, but may be considered for other applications (second life of the battery)

Second-life of EV battery and aftermath

- Once the batteries reach 70%-80% of their initial capacity, they can be used in Fixed Storage applications like UPS and grid-storage
- While Mobile / EV batteries are constrained in terms of Size and Weight, Fixed storage is not as constrained

Aftermath of second-life of batteries

- Recycling: recover all materials with ZERO effluent and build new batteries
- Electronic gadgets / smartphones / lap-tops batteries may be too small for second life usage and may directly go for recycling

Li –ion Battery

- A **lithium-ion battery**, or **Li-ion battery**, is a type of [rechargeable battery](#) that uses the reversible [intercalation](#) of Li^+ ions into electronically [conducting](#) solids to store energy.
- **Intercalation** is the reversible inclusion or insertion of a [molecule](#) (or ion) into [layered materials](#) with layered structures. Examples are found in [graphite](#) and [transition metal dichalcogenides](#)

Li-Ion Battery Chemistries

Cathode	Anode	Characteristics
LCO (LiCoO ₂)	Graphite	Used in cell-phones; Cobalt-rich and expensive
NMC* (LiNi _x Mn _y Co _z O ₂)	Graphite	Most commonly used EV battery; NMC811 has minimal Cobalt, Nickle rich version attempts even smaller Cobalt
NCA (LiNiCoAlO ₂)	Graphite	Similar to NMC; less expensive, lower number of cycles; used by Tesla as its battery size is large
LFP (LiFePO ₄)	Graphite	Safer than NMC; limited by specific energy ; used to be dominant in China, now on way-out
NMC	LTO (Li ₄ Ti ₅ O ₁₂)	LTO anode gives much longer life-cycles and temperature tolerance, SAFE, but poor-specific-energy; high costs
LFP	LTO	Similar to NMC-LTO



Classification	Definition
<i>Cell</i>	Basic unit of LI-ion battery that exerts electric energy by charging and discharging.
<i>Module</i>	A group of cells assembled out into a frame to protect the cells from external shocks, heat or vibration.
<i>Pack</i>	Final battery systems installed to an electric vehicle.

Battery Pack

- Number of cells assembled to form a battery-pack for required voltage and capacity

Design considerations for Pack

- Thermal design must remove the heat generated from the pack immediately

Cells- temperatures need control

- Mechanical design should include safety considerations

Right Pressure needs to be applied to cells, else they will bulge

- Battery Management System (BMS)

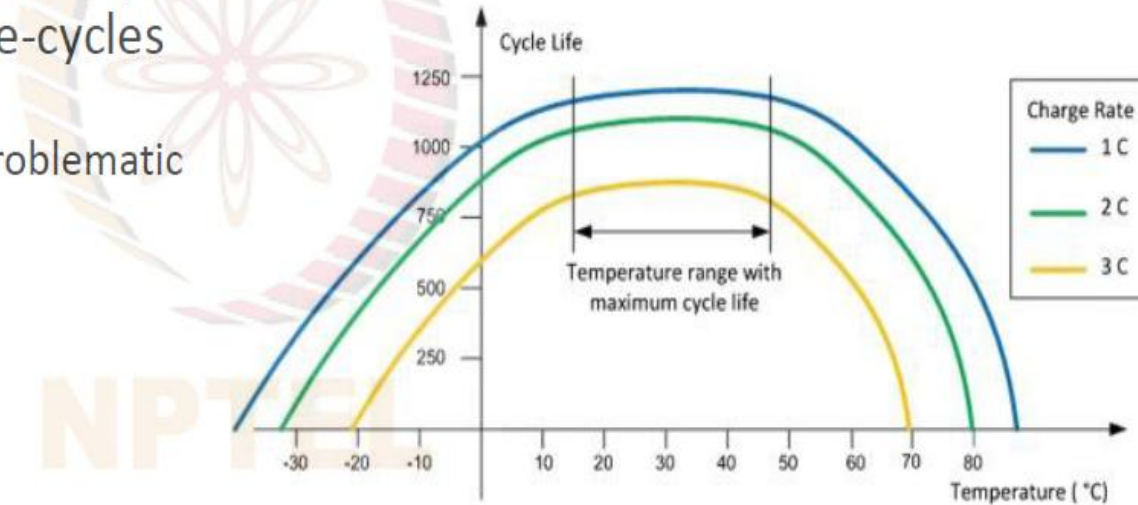
Only balanced cells used in a pack: requires voltage/current/temperature monitoring of each cell and balancing cells during charging as well as discharging

Pack should get cut off if the temperature increases: key to safety

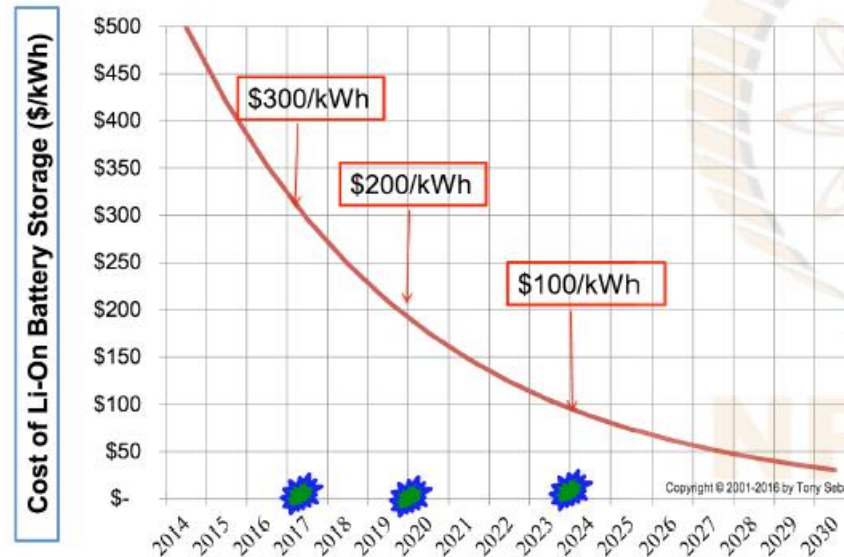
Temperature Dependence of life

Higher temperature (40°C or more)
implies smaller number of life-cycles

- **Lower** temperature is equally problematic
(less than 0°C is as bad)



Battery Chemistry



Most popular large batteries used to be Lead-Acid till a few years back

- Ni-Cad and Ni-M Hydride came up later

Li-Ion Battery cells emerged

- First for cell-phones and lap-tops
- Then became dominant for EVs
- And the increasing energy density and falling prices made it dominant today

Cost-driver: Energy-density continuously increasing

Gravimetric ED of NMC and NCA cells is in between 250 to 300 Wh/kg today

- Towards 400 to 500 Wh/kg in coming years: NMC with Graphite-Silica anode

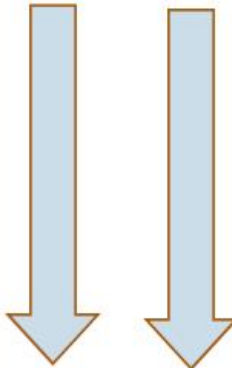
Volumetric Energy Density of NMC cells touching 500 Wh/litre

- Other variants of Li-battery may emerge to drive energy density higher

Cost of battery inversely related to its energy density

- *Main driver of cost reduction*
- Higher energy-density: lower use of materials like Lithium, Cobalt, Nickel, Manganese, Graphite

Energy Density (Wh/kg)		Cell-price per kWh	
2011:	80		\$800
2015:	140		\$275
2018:	220		\$140
2020:	310		\$110



Other Lithium Batteries I

Lithium-air (Li-air)

Theoretical specific energy of 13kWh/kg, on par with gasoline: also other metal-air (like Al-air) -- called breathing air batteries

- Even if we hit quarter: equivalent to gasoline because EV has higher efficiency
- Only 50 cycles today

Lithium-metal (Li-metal)

Has been demonstrated with a capacity of 300 Wh/kg. Decent cycle-life (2500 cycles) and rapid Charge.

- Challenges: uncontrolled lithium deposition causing dendrite growth that induces safety hazards by penetrating the separator and producing an electrical short. A solution to inhibit the growth of dendrite may be imminent. Also need other precautions including non-flammable electrolytes, safer electrode materials and stronger separators.

Other Lithium Batteries II

Solid-state Lithium

Anode with pure lithium and solid polymer electrolyte or a ceramic separator.
High Energy Density

Challenges: problem of metallic filament (dendrite) formation even with dry polymer and ceramic separators. Plus **poor conductivity at cool temperatures**, difficulty to diagnose problems within the cell and low cycle count (**100 cycles**)

Lithium-sulfur (Li-S)

high specific energy of **550Wh/kg** and specific power of 2,500W/kg, have good cold temperature discharge. The battery is environmentally friendly; sulfur, the main ingredient, is abundantly available. Reasonable costs

Challenges: **Poor charging and cycle life**

Other similar batteries

Sodium-ion (Na-ion)

Sodium-ion (inexpensive Sodium) lower-cost alternative to Li-ion, can be completely discharged. Poor specific energy of 90Wh/kg, but low cost. Development needed to improve the cycle count and solve large volumetric expansion when fully charged

Lithium-manganese-iron-phosphate (LMFP)

Capacity 15% over LFP, specific energy 135Wh/kg and 5000 cycle life. Inexpensive.

Cell Balancing

- Battery Cell Balancing also means **battery redistribution to improve the overall potential of the battery pack** and emphasize each cell's longevity. Cell Balancing enhances the State of Charge (SOC) of your battery.
- An imbalance is created when every cell in the connected series of the battery pack depicts a different SOC. Such an imbalance results in the overall battery capacity equal to the weakest cell in the battery pack.
- However, to optimize the battery life, we must ensure that we bring a cell balancing to equalize the overall battery of each cell in the pack.

Cell Balancing

- **FACT:** No two cells (even if they have the same model number, manufacturer, production) have the same SoC, discharge rate, impedance, temperature, and capacity.
- Active Cell Balancing, Passive Cell Balancing