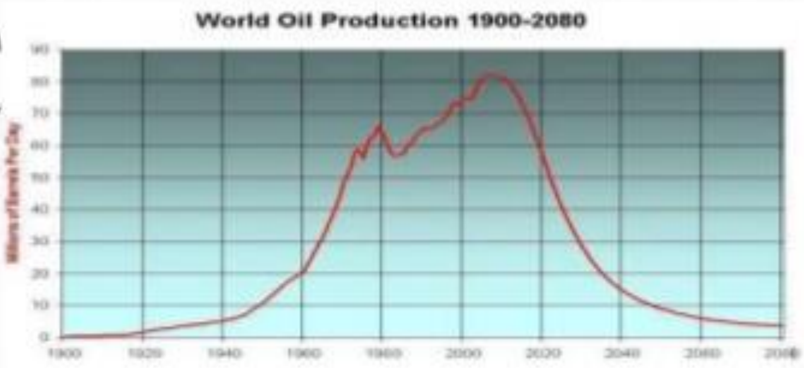
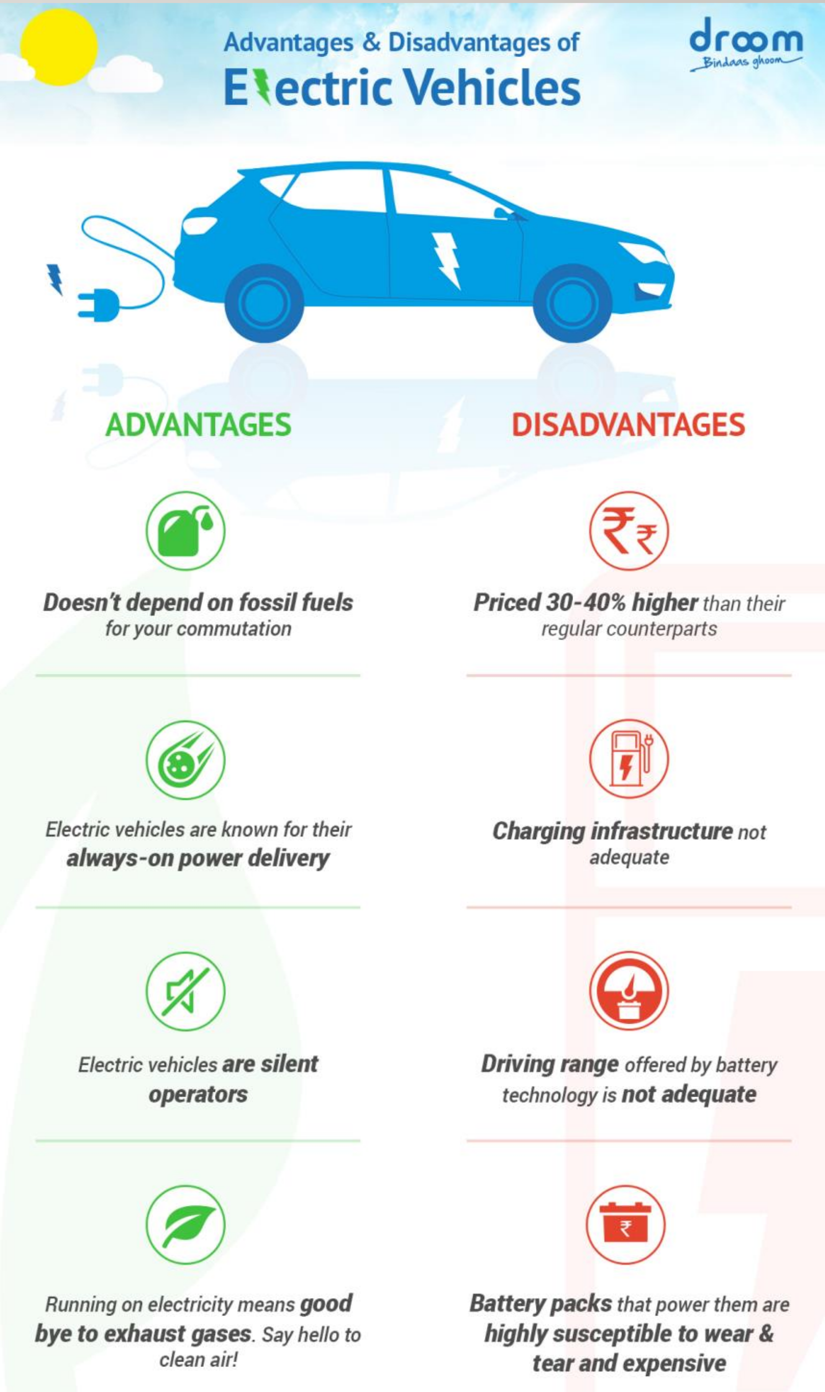
ELECTRIC VEHICLE

Need Electric and Hybrid vehicles

- Over dependence on petrol/diesel
- Rising petrol/diesel prices
- Pollution and the resultant global warming
- Noise in conventional vehicles
- Need for alternate power sources
- Need for Eco friendly v
- EV, HEV - The solutio





ELECTRIC VEHICLE

- **EVs refers to any vehicle powered, in part or in full, by a battery that can be directly plugged into the mains.**

PURE ELECTRIC VEHICLE

Pure-EVs are electric vehicles powered only by a battery.

PLUG-IN HYBRID ELECTRIC VEHICLES (PHEV)

- **Have an internal combustion engine (ICE) but also a battery range in excess of 10 miles.**

- **After the battery range is utilized, the vehicle reverts to full hybrid capability (utilizing both battery and ICE power) without compromising the range.**

Figure 1.2 Volkswagen Golf GTE – PHEV

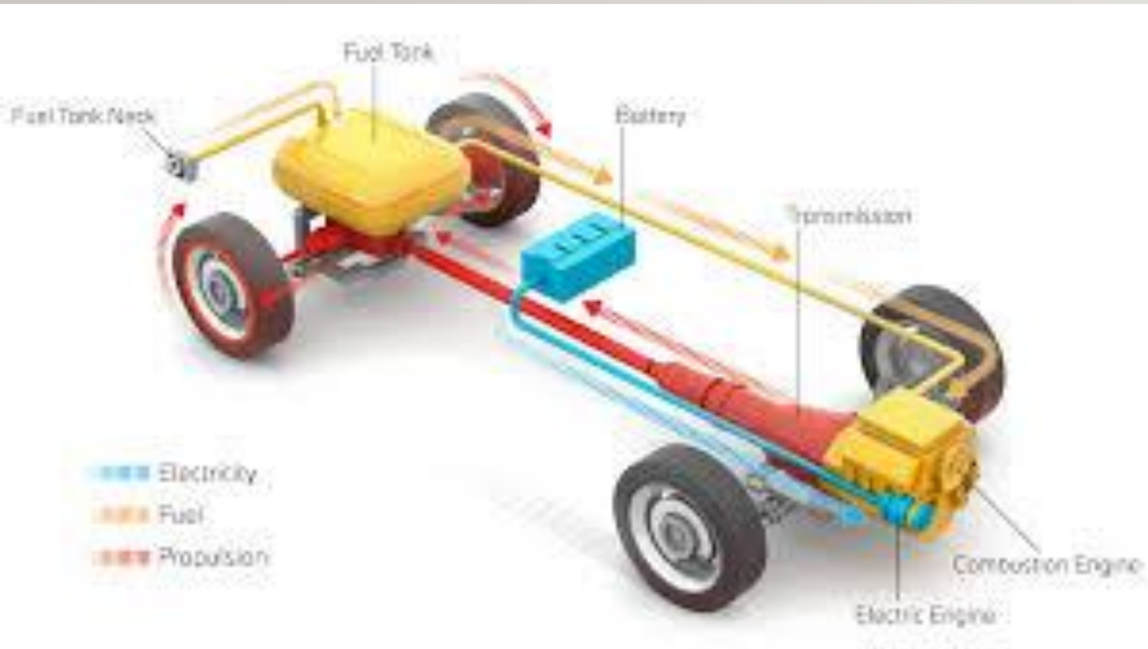
EXTENDED-RANGE ELECTRIC VEHICLES (E-REV)

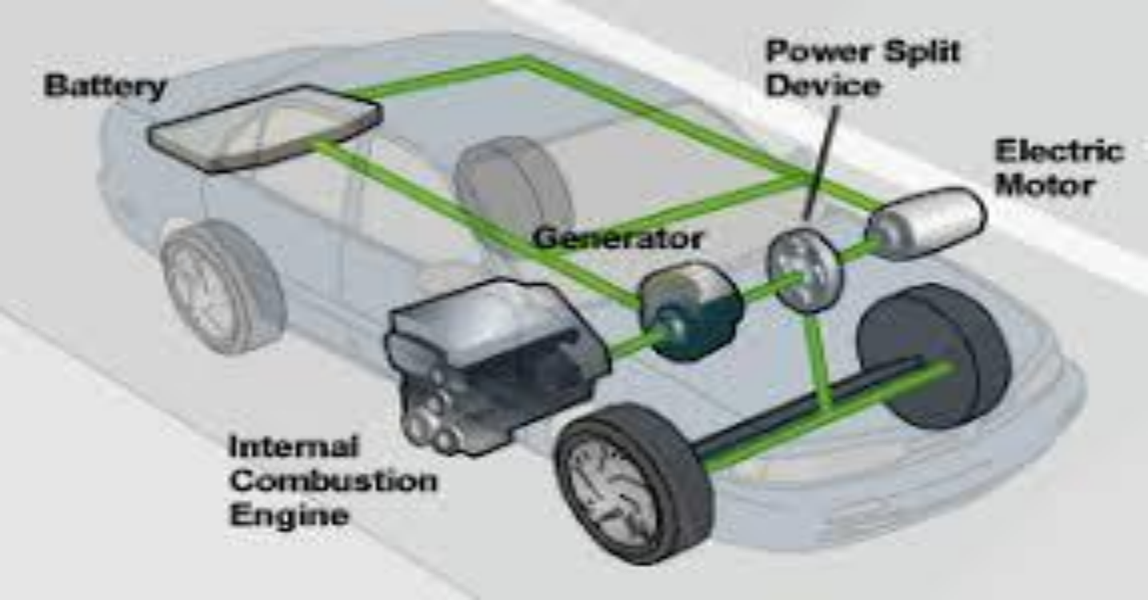
Figure 1.3 Chevrolet Volt – E-REV (Source: GM Media)

- **E-REVs are similar to pure-EVs but with a shorter battery range of 50 miles. However, range is extended by an ICE-driven generator providing many additional miles of mobility.**

- **With an E-REV, the propulsion is always electric, unlike a PHEV where the propulsion can be electric or full hybrid.**

HYBRID ELECTRIC VEHICLES (HEV)





- **Powered by both IC Engine & Battery.**

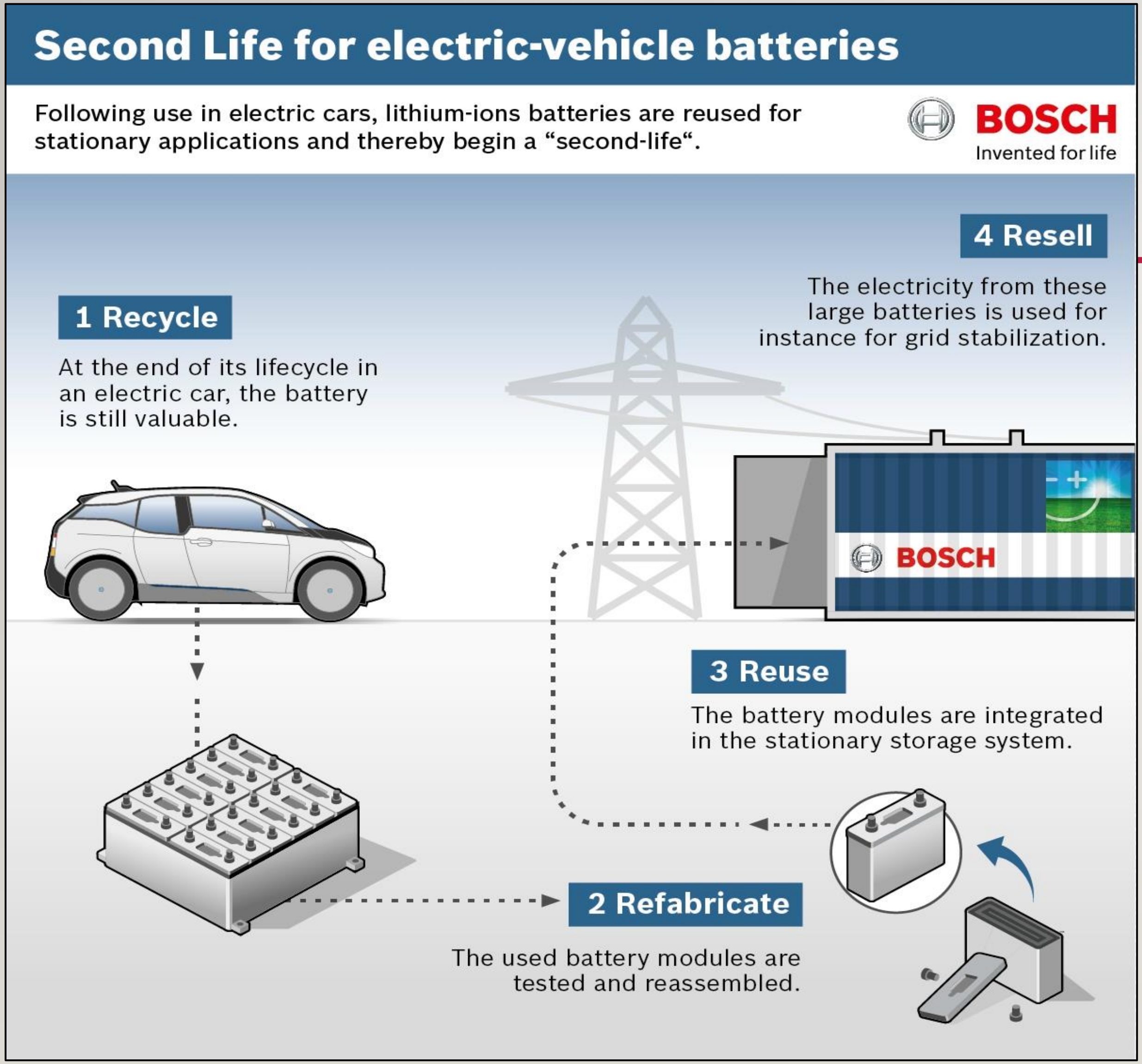
- **Power source is selected automatically by the vehicle depends on speed/load/battery charge.**

- **Battery cannot be plugged-in & charge is maintained by regenerative braking supplemented by IC Engine.**

COMPARISON OF COSTS

Term, mileage, fuel cost	ICE	Pure-EV	PHEV	Notes
Annual mileage	10,000	10,000	10,000	
Cost of fuel (£/gallon or £kW/h)	£5.70	£0.05	£5.70/£0.05	Electricity (£/kWh). Higher value used for calculation. Lower if overnight charge or solar is used
Official combined cycle mpg	68 mpg	150 Wh/km	166 mpg	Electricity consumption (Wh/km)
'Real world' mpg	50 mpg	175 Wh/km 0.28 kWh/mile	100 mpg[6]	Real-world consumption
Total fuel costs	£1,140	£140	£570	(annual miles × fuel cost/mpg) (annual miles × fuel cost × kWh/mile)
Vehicle cost information				
Purchase price	£28,000	£34,000	£35,000	Estimates based on current list prices
Plug-in car grant		–£5,000	–£5,000	A grant to reduce cost by 25% (up to £5,000)
Net purchase price	£28,000	£29,000	£30,000	
Depreciation cost/year	£8,400	£8,700	£9,000	30% used – this will vary however
Residual value	£19,600	£21,300	£21,000	
Service, maintenance and repair	£190	£155	£190	Based on average of published figures
Other information				
Vehicle Excise Duty and Registration Fee	£30	£0	£0	
TOTAL COST	**£9,760**	**£8,995**	**£9,760**	**First year**

END OF LIFE



ELV Directive encourages good product design.

- **Eg. Avoiding the use of harmful heavy metals.**
- **Increasing the use of recycled materials.**
- **Designing the car components and materials for easy reuse or recycling.**

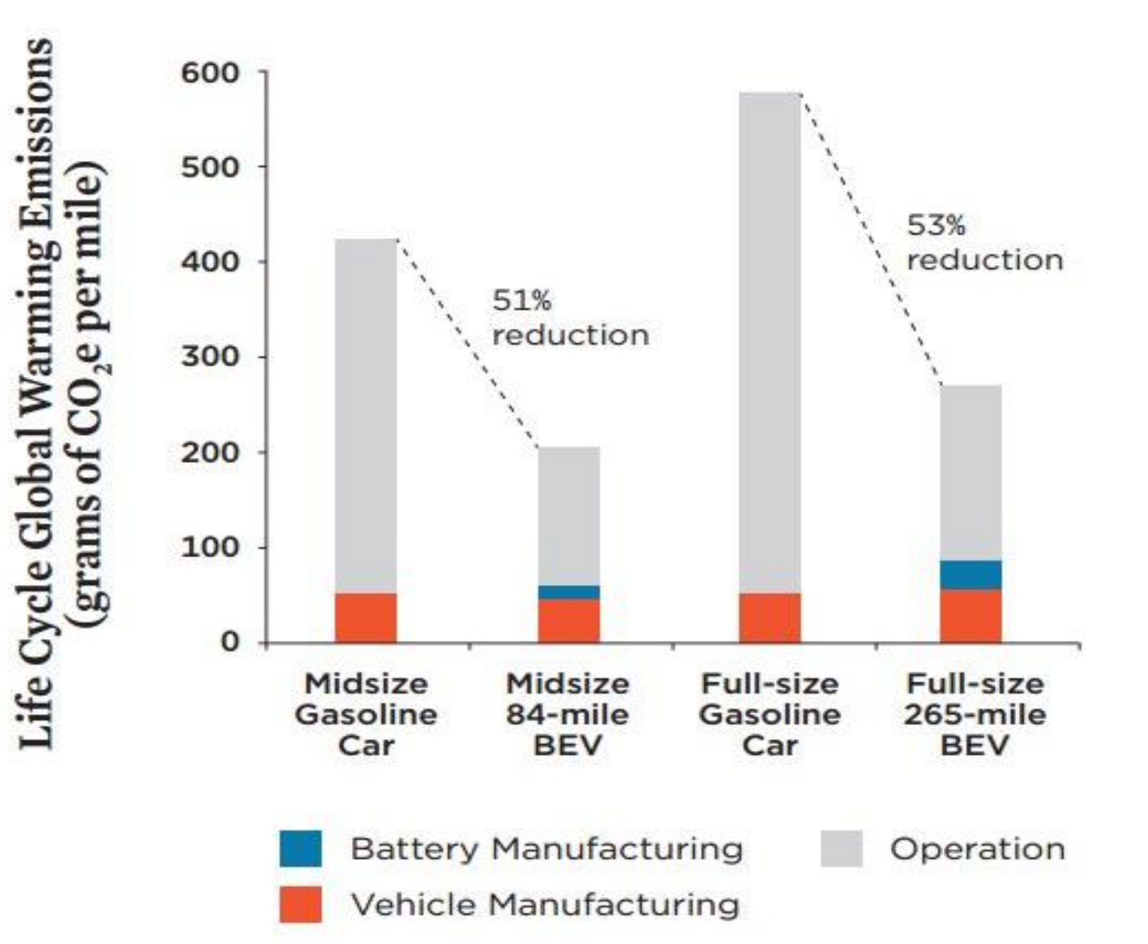
EMISSIONS

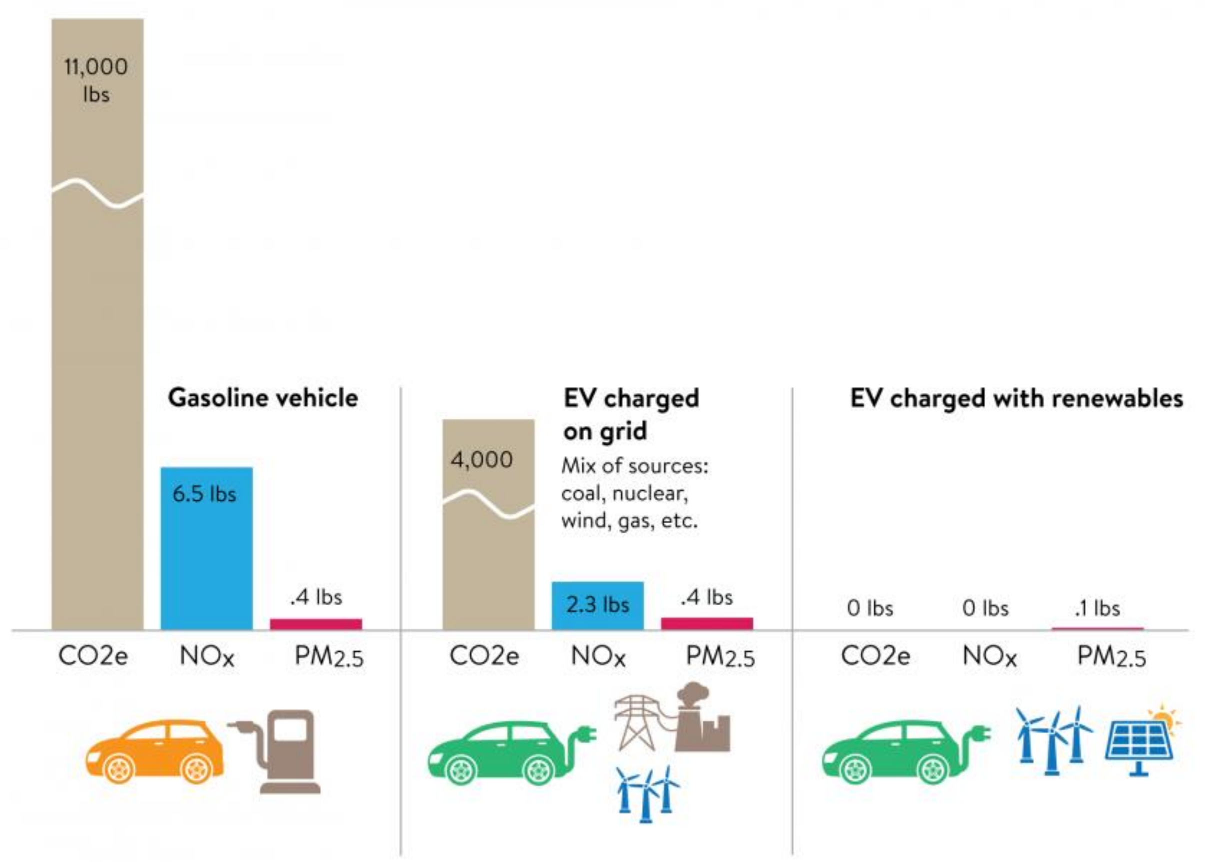
	Tank-to-wheel	Well-to-tank	Well-to-wheel
Pure-EV	0 g CO_2/km	77 g CO_2/km	77 g CO_2/km
ICE	132.3 g CO_2/km	14.7–29.0 g CO_2/km	147.0–161.3 g CO_2/km

Key Fact

Electric vehicles have zero emissions at the point of use, so-called ‘tank-to-wheel’.

Life Cycle Global Warming Emissions from the Manufacturing and Operation of Gasoline and Battery-Electric Vehicles





CABLES

Figure 4.31 VW Golf-e showing some of the orange cables

- Cable should be insulated to prevent contact and short circuits.
- Most cables are made from many strands of copper wire as this offers low resistance and retains flexibility.
- Insulation is normally a form of PVC.
- High-voltage cables require greater insulation to prevent voltage leakage, the risk of harm if touched is very high.
- Stickers with various symbols are used as a warning together with the bright orange colour.

CABLES

Figure 4.32 Orange cables and warning stickers on a Golf GTE

Power equals voltage multiplied by current (P = IV).

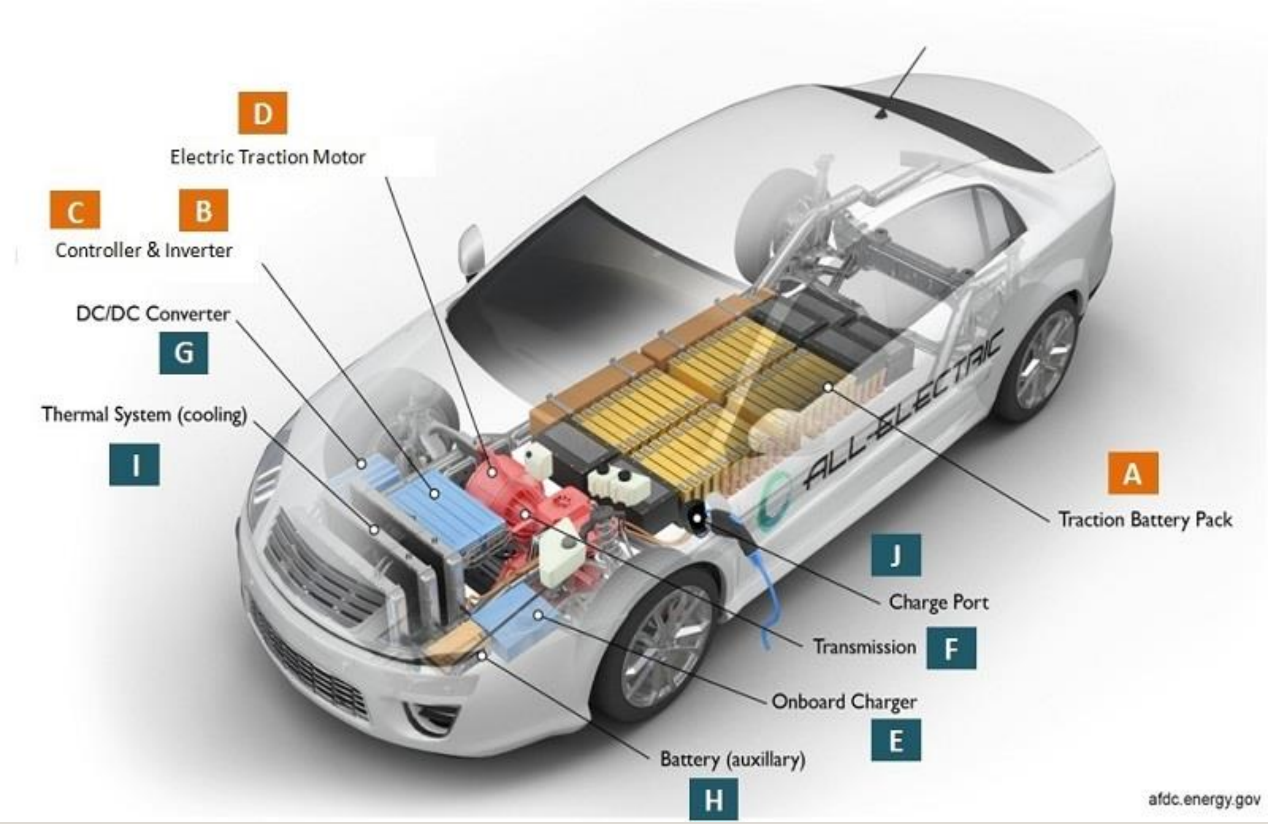
- To deliver high power, they have to carry high current – even at high voltage!

- Assume a voltage of 250 V & cable has to deliver say 20 kW then 20,000/250 = 80 A.

- Under hard acceleration i.e., this is even higher: 80 kW would require a current of 320 A.

- To meet this cables are quite thick as well as well insulated.

COMPONENTS OF EVs

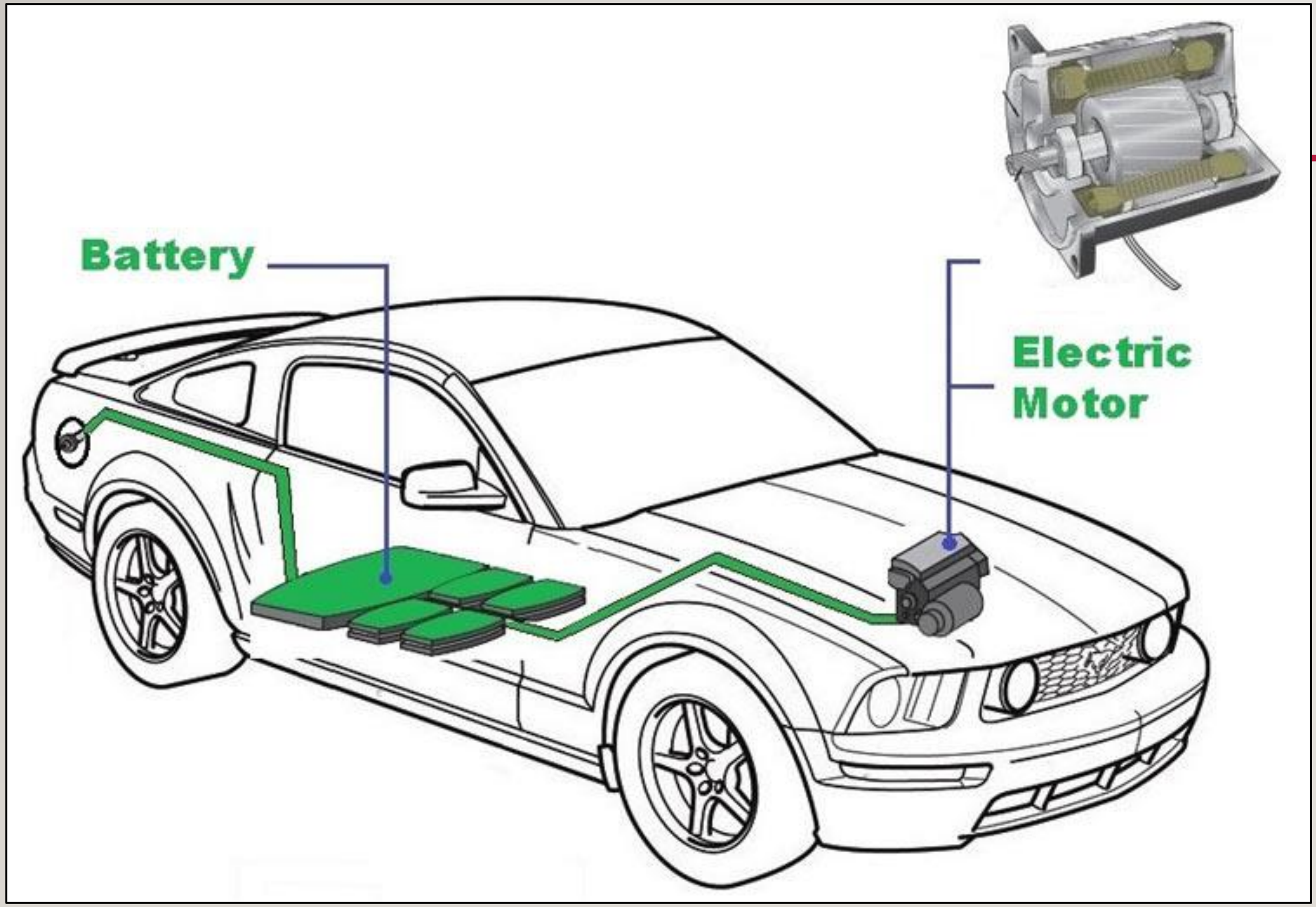


- **Battery**
- **Motor**
- **Control Unit (Power Electronics)**
- **Charger**
- **Invertor**
- **Battery Management Controller**
- **Driver display interface**

COMPONENTS OF EVs

- **Battery:** Most common battery is lithium-ion & installed under body of the car which weighs over 300 kg.
- Complete battery pack consists of 200–300 cell modules, cooling system, insulation, junction box, battery management and shell.
- Battery is able to withstand impacts and a wide range of temperatures.
- Capacity: 20-25 kWh

COMPONENTS OF EVs



- **Motor**: Converts electrical energy into kinetic energy or Movement.

- Type of AC synchronous motor supplied with pulses of DC.

- Rated in the range of 85 kW on pure-EVs.

COMPONENTS OF EVs

- **Control unit**: Called as power control unit or motor control unit.

- Responds to signals from driver (brake, acceleration etc.) and causes the power electronics to be switched accordingly. The control makes the motor drive the car or become a generator and charge the battery.

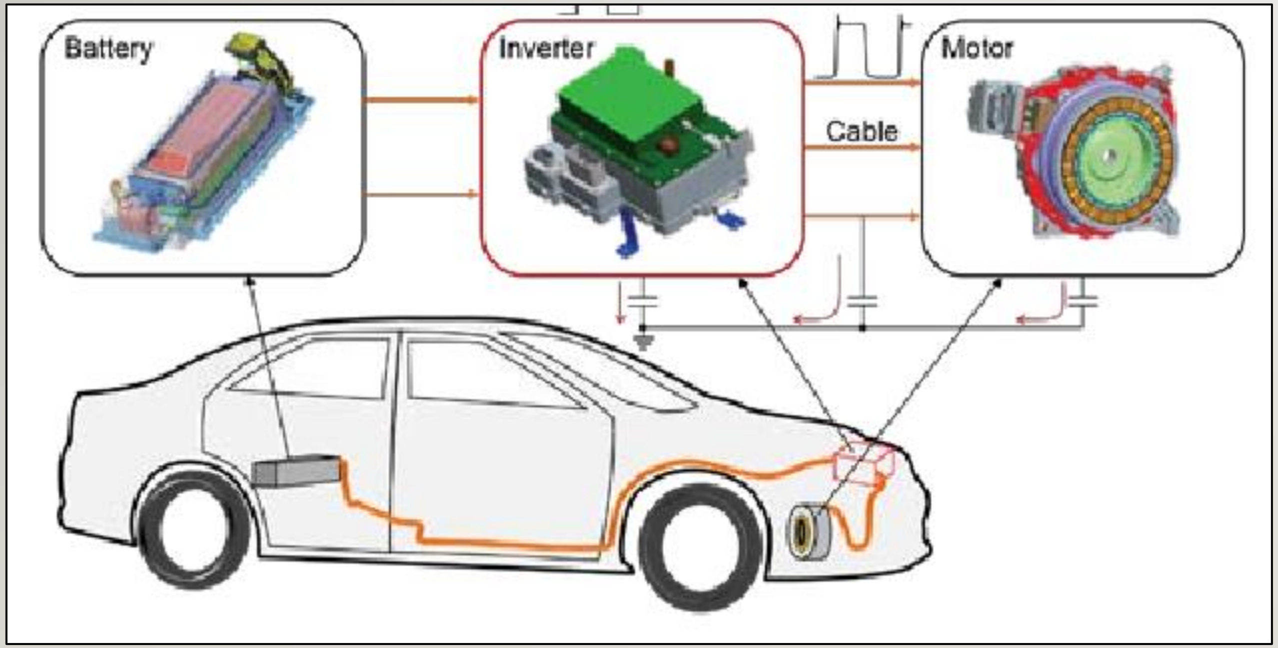
- Also be responsible for A/C and brakes.

COMPONENTS OF EVs

- ✓**Charging unit:** Usually located near where the external power source is connected.

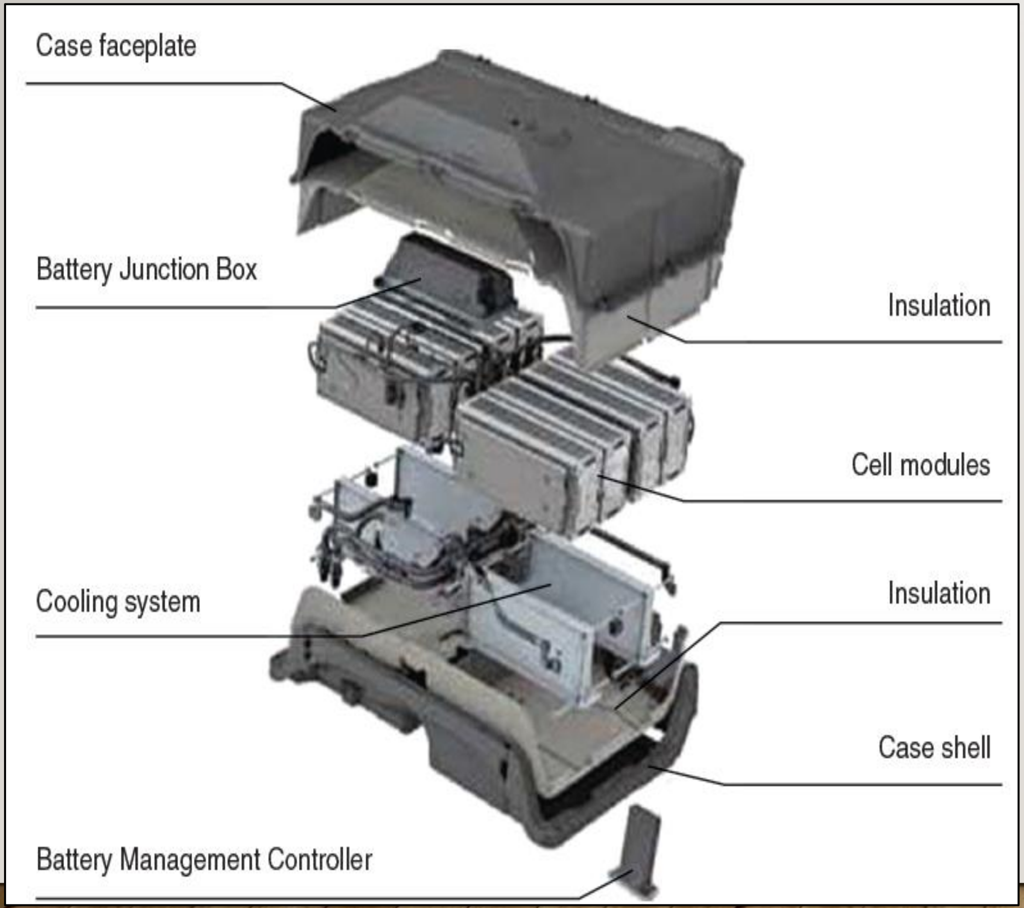
- ✓Converts and controls the 'mains' voltage (typically 230/240 V AC in Europe and 120 V AC in the USA) to a suitable level for charging battery cells.

COMPONENTS OF EVs



- **Invertor:** An electronic device that changes DC from the battery to AC to drive the motor.
- Also does this in reverse for regenerative charging.
- Sometime the same or a separate inverter is used to supply the 12-V system.

COMPONENTS OF EVs



- **Battery management controller**: Monitors and controls the battery. Determines the state of charge of the cells.
- It regulates the temperature and protects the cells against overcharging and deep discharge.
- Electronically activated switches are included that disconnect the battery system when idle and in critical situations such as an accident/fire.

COMPONENTS OF EVs

Figure 4.36 Setting the maximum charge current

Driver interface: To keep the driver informed, a number of methods are used.

- Most common now is a touch screen interface where information can be delivered as well as allows driver to change settings such as charge rate.

LAYOUT OF EVs

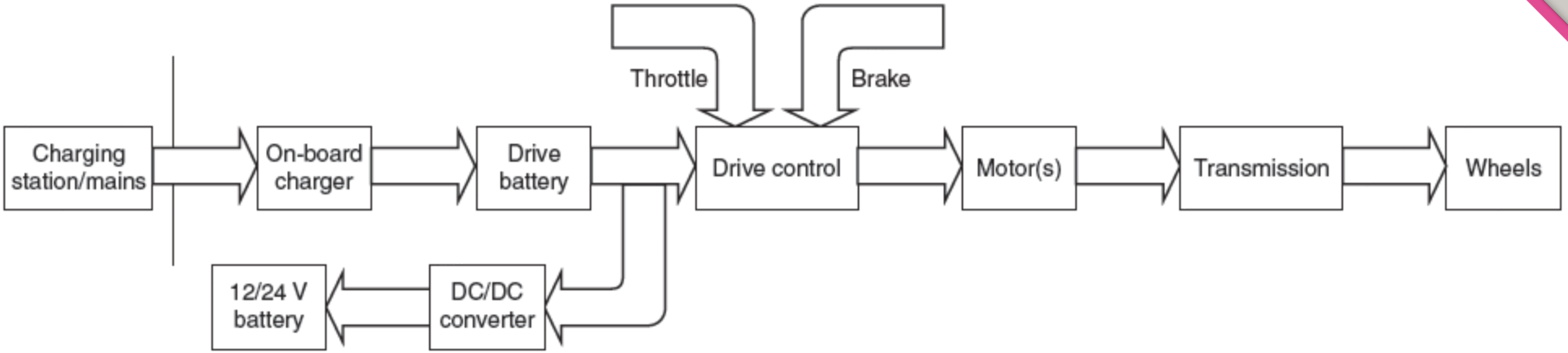


Figure 4.7 Generic electric vehicle layout

BATTERY RANGE

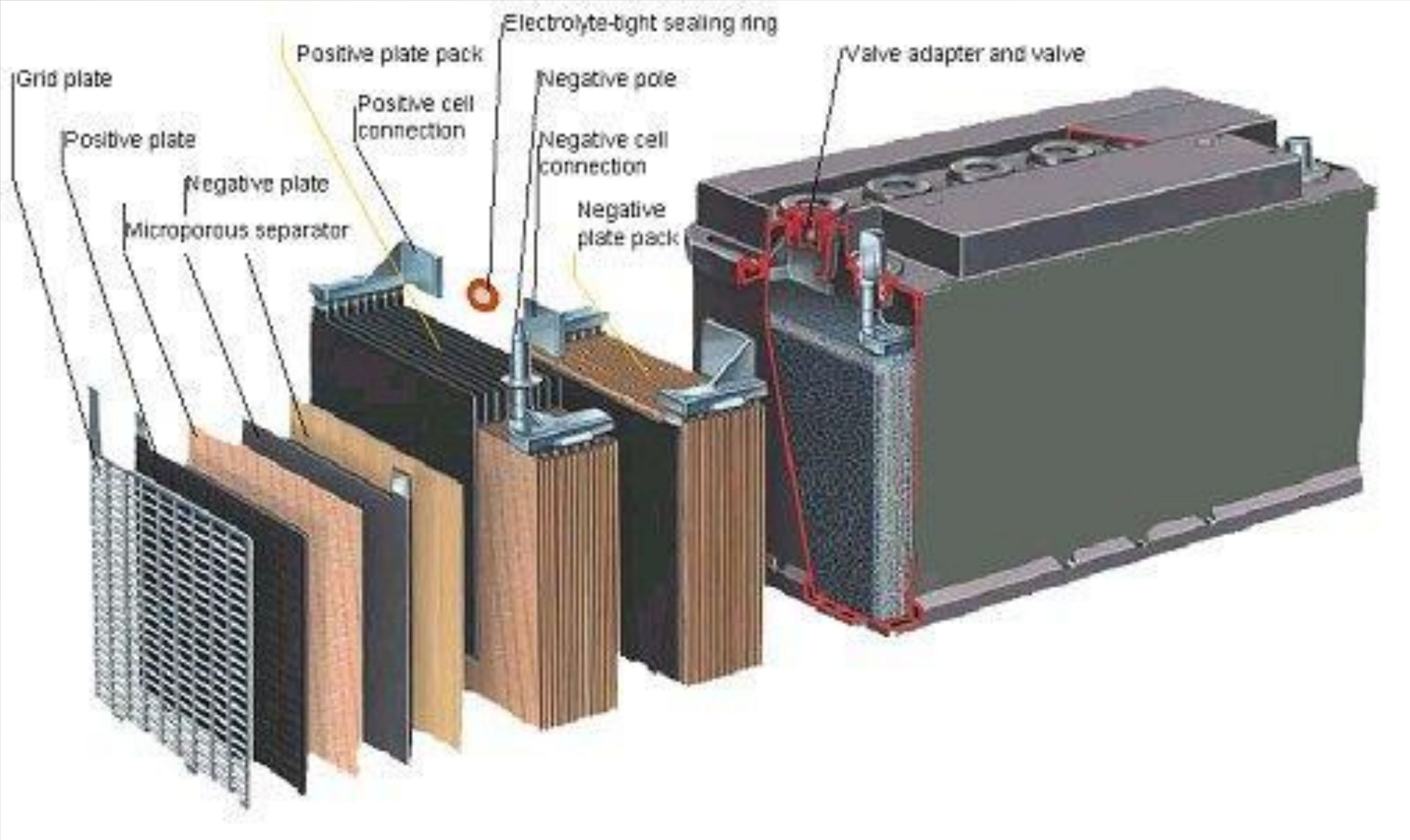
- Distance covered by an E-Vehicle pre battery charge.
- Lead-acid batteries are capable of upto 130 km/charge.
- Li-ion batteries upto 480 km.

BATTERY RANGE

- **Smooth driving with gentle acceleration and minimal braking has the most impact on battery range.**

- **Range is also affected by cold weather as well as the use of air conditioning (heating or cooling)**

BATTERY CROSS SECTION



2 CLASSES OF BATTERIES

- PRIMARY CELLS
- SECONDARY CELLS

PRIMARY CELLS

- CANNOT BE RECHARGED
- CHEMICAL PROCESS NOT REVERSABLE
- ZINC CARBON (1.5V)
- ALKALINE (1.5V)

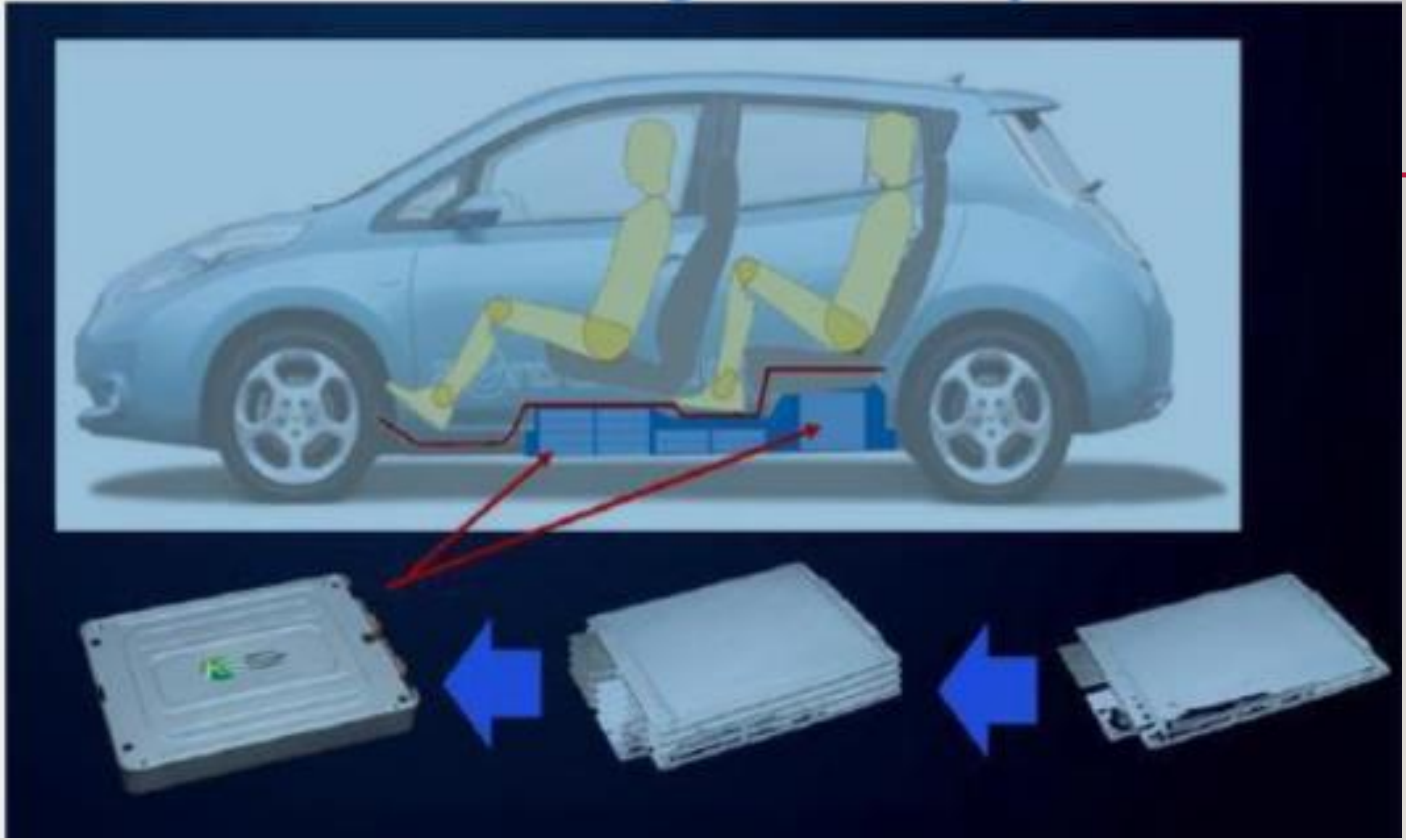
SECONDARY CELLS

- CAN BE RECHARGED

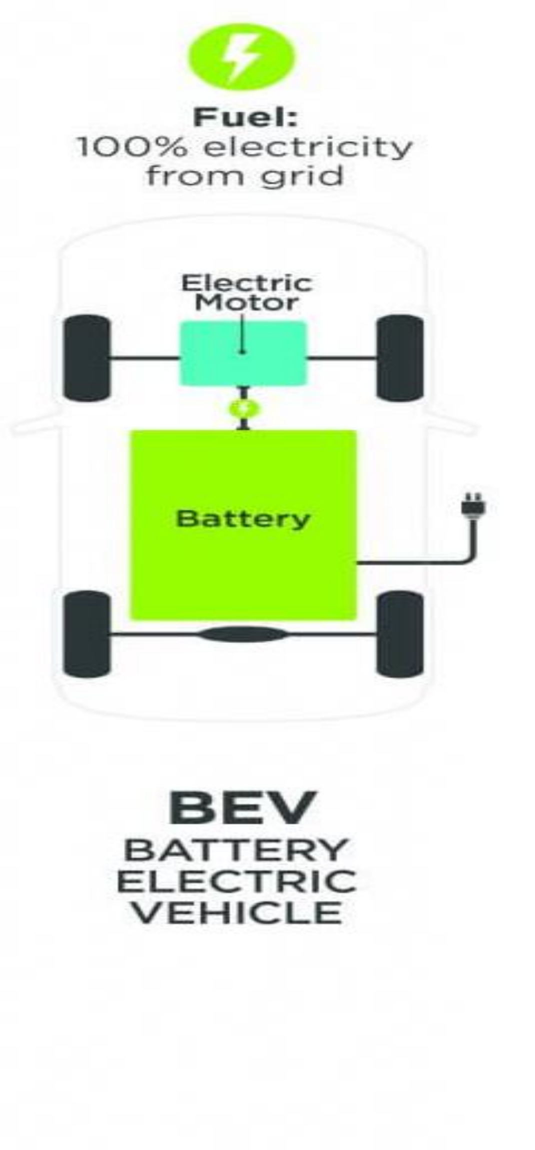
- CHEMICAL REACTION REVERSABLE

- LEAD ACID (2.0V)
- NICKEL - CADMIUM (1.2V)
- NICKEL - METAL HYDRIDE (1.2V)
- LITHIUM – ION (3.3V)

Positioning of battery in EV



BATTERY - TYPES



- **Lead-acid (Pb-PbO_2) batteries**
- **Alkaline (Ni-Cd, Ni-Fe & Ni-MH) batteries**
- **Sodium-Nickel Chloride (Na-$NiCl_2$) batteries**
- **Sodium-Sulpur (Na-S) batteries**
- **Lithium-ion (Li-ion) batteries**

BATTERY - REQUIREMENTS

- Safe
- High power
- High capacity
- Small and light
- Large format
- Long Life
- Low overall cost

LEAD-ACID BATTERY

- Negative electrodes contain Pb while the positive plates have PbO_2 as active material in charged state.
- Electrodes are immersed in an electrolyte of sulphuric acid.
- When being discharged the lead and the lead dioxide reacts with the sulphuric acid.
- $Pb + PbO_2 + 2H_2SO_4 \longleftrightarrow 2PbSO_4 + 2H_2O$
- Lead sulphate is formed on the electrodes and the electrolyte loses its dissolved sulphuric acid and becomes water.
- Energy is released during the chemical reaction and when energy is added the process will reverse.

LEAD-ACID BATTERY

Modern vehicle battery

- **Best choice for low-voltage motor vehicle.**
- **Low cost and high energy density.**
- **Nominal 12 V battery consists of six cells connected in series. Each cell, producing about 2 V, is housed in an individual compartment within a polypropylene case.**
- **Modern batteries are sealed.**

LEAD-ACID BATTERY

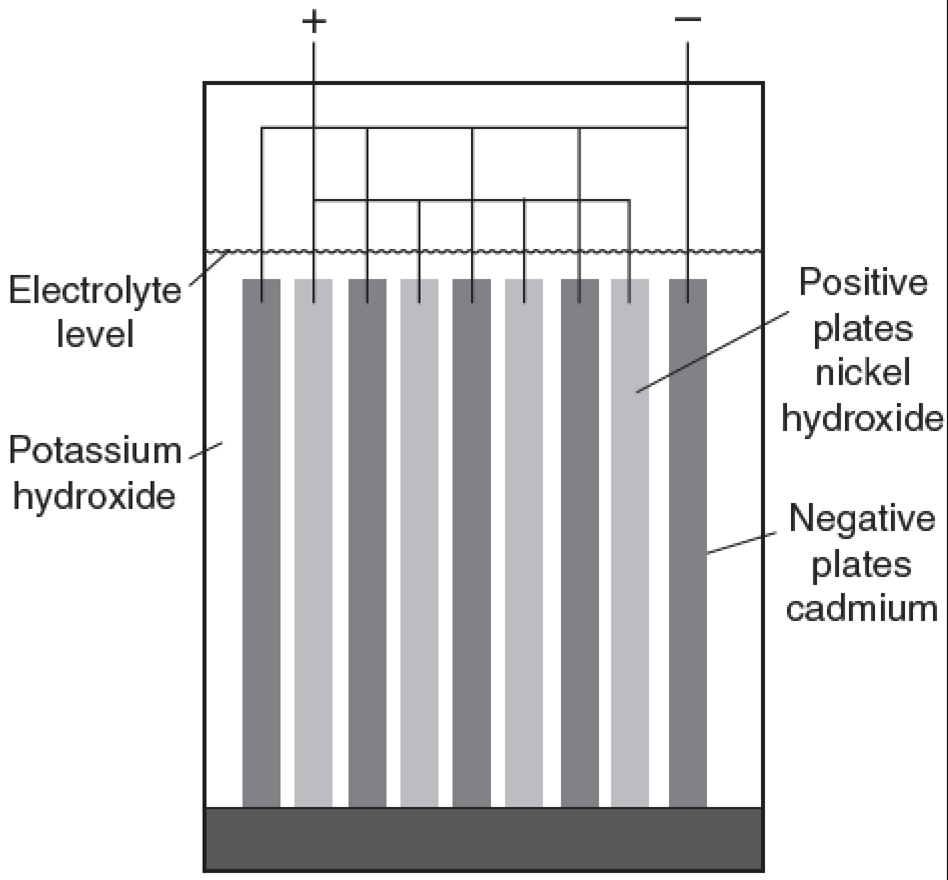
Precautions

- Clean corrosion from terminals using hot water.

- Terminals should be smeared with petroleum jelly or Vaseline.
- Battery tops should be clean and dry.
- If not sealed, cells should be topped up with distilled water 3 mm above the plates.

ELECTRIC VEHICLE

ALKALINE BATTERY



Simplified representation of a NiCad alkaline battery cell

TYPES

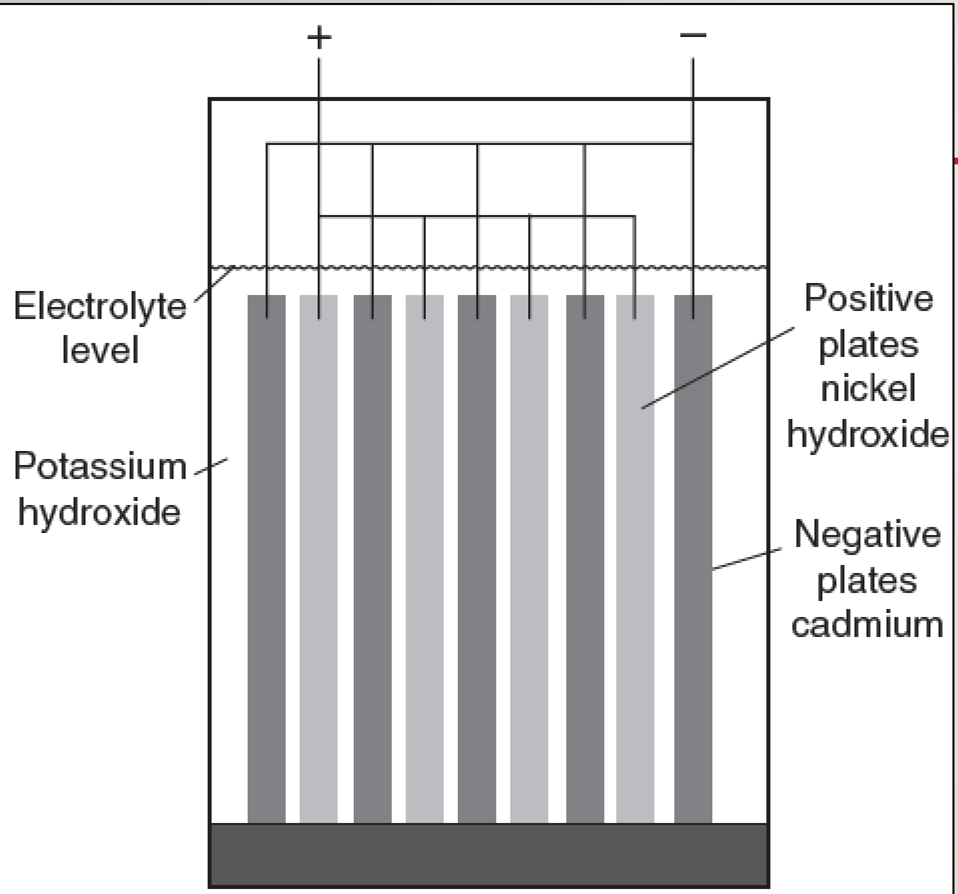
- **Ni-Cad Battery**
- **Ni-Fe Battery**
- **Ni-Zn Battery**
- **Ni-Metal hydride (Ni-MH) Battery**

Ni-Cd Battery

- **Positive plate – Nickel hydrate (NiOOH)**
- **Negative plate – Cadmium (Cd)**
- **Electrolyte – potassium hydroxide (KOH) & water (H_2O).**

$$2NiOOH + Cd + 2H_2O + KOH = 2Ni(OH)_2 + CdO_2 + KOH$$

Ni-Cd BATTERY



Simplified representation of a NiCad alkaline battery cell

- **During charging oxygen moving from negative plate to positive plate, and the reverse when discharging.**
- **When fully charged, the negative plate becomes pure cadmium and the positive plate becomes nickel hydrate.**

Key Fact

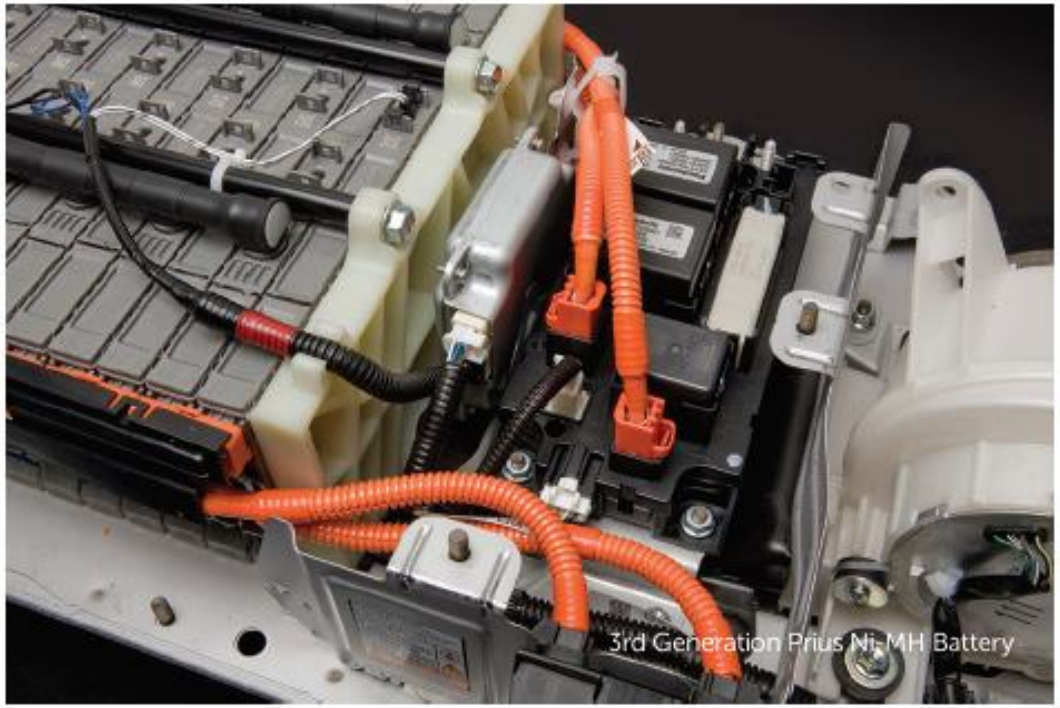
NiCad batteries do not suffer from over-charging because once the cadmium oxide has changed to cadmium, no further reaction can take place.

NICKEL-METAL HYDRIDE BATTERY

$$MH + NiOOH \longleftrightarrow M + Ni(OH)2$$

- Cathode – Nickel oxyhydroxide

- Anode – H_2 absorbing alloys



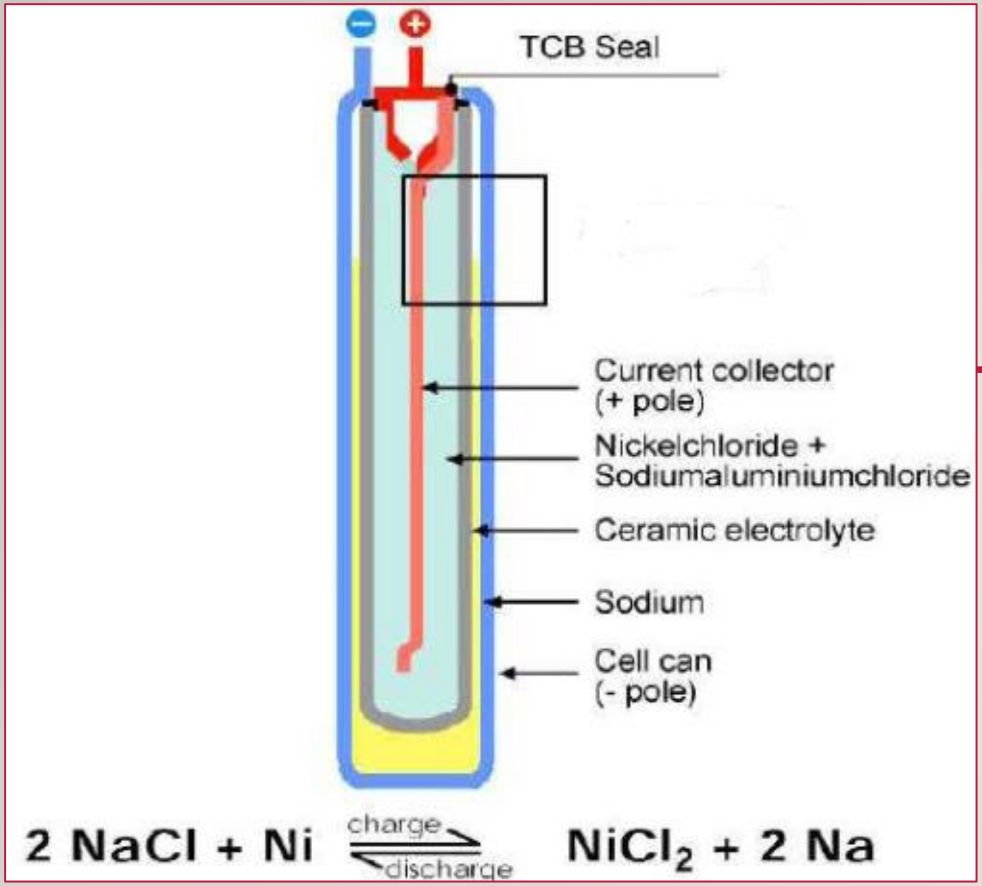
Toyota NiMH battery and management components (Source: Toyota)

- Electrolyte – KOH
- Nickel oxyhydroxide becomes Nickel hydroxide during discharge.
- At negative electrode H_2 is released from metal hydride producing water and e^- during discharge.

- Energy density of NiMH is double than that of a lead–acid battery & less than Li-ion Battery.

- No Cd & hence environmental friendly.

SODIUM-NICKEL CHLORIDE BATTERY

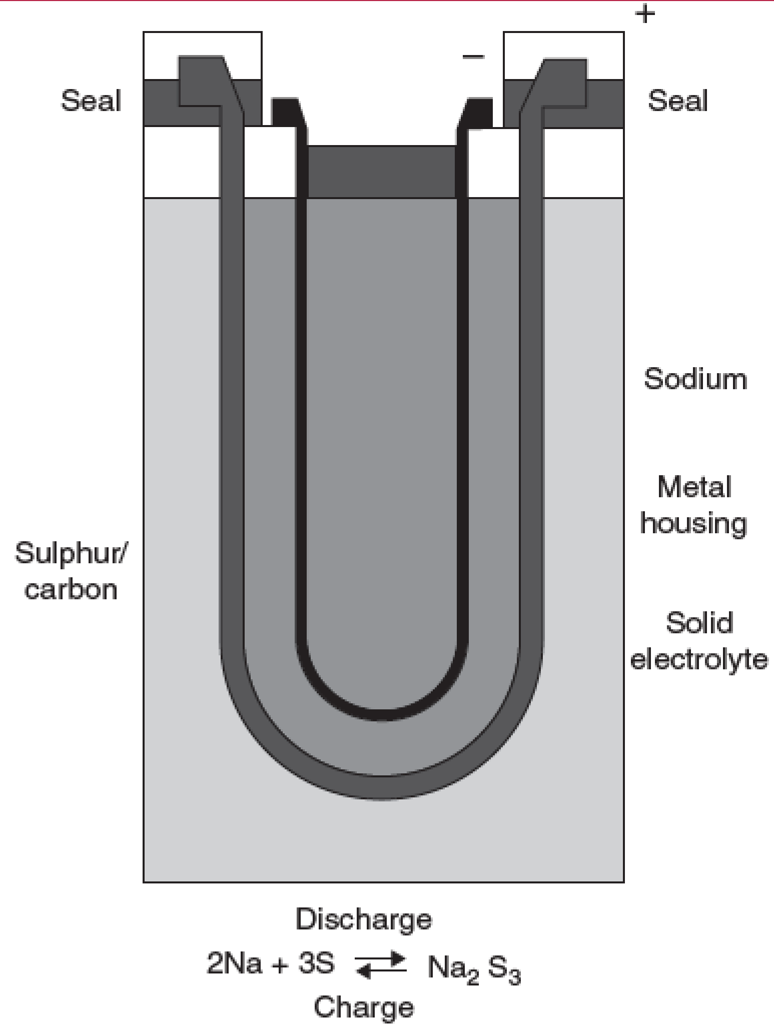


- **Molten salts as an electrolyte and offers both high energy density and a high power density.**
- **This is due to very high ionic conductivity of molten salt, which is three orders of magnitude greater than that of sulfuric acid in a lead–acid battery.**
- **Positive electrode made of solid $NiCl_2$ & negative electrode of molten sodium. Central positive electrode is impregnated in a liquid electrolyte of sodium-aluminium chloride surrounded by a ceramic electrolyte.**
- **During discharge Ni & NaCl are transformed into salt and nickel.**

SODIUM-NICKEL CHLORIDE BATTERY

- Lifetime is more than 10 Years.
- Downsides to Zebra battery - Poor power density (<300 W/kg) & Requirement of having to heat the electrolyte to about 270 °C.
- Zebra batteries have been used in commercial vehicle since it entered production in 2006

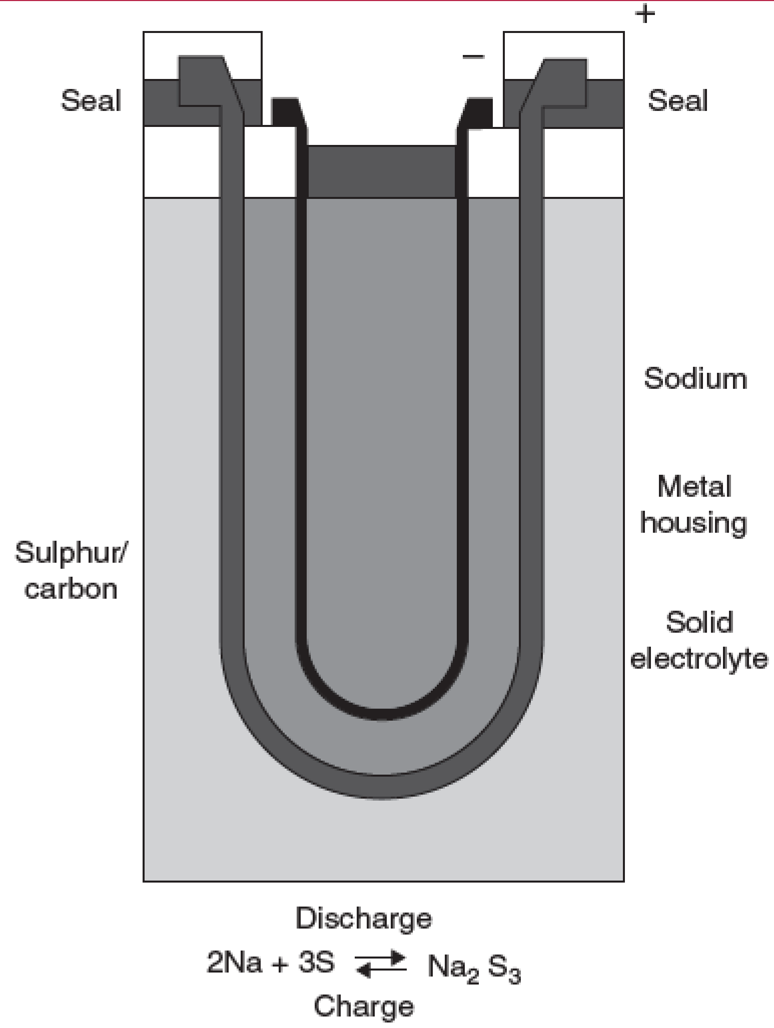
SODIUM-SULPHUR BATTERY



Sodium–sulphur battery

- **Cathode: Liquid sodium; Anode: Sulphur electrode**
- **Solid electrode of alumina (a form of aluminium oxide).**
- **Major problem with this system is that the running temperature needs to be 300–350°C.**
- **A heater rated at a few hundred watts forms part of the charging circuit & maintains the battery temperature when the vehicle is not running.**

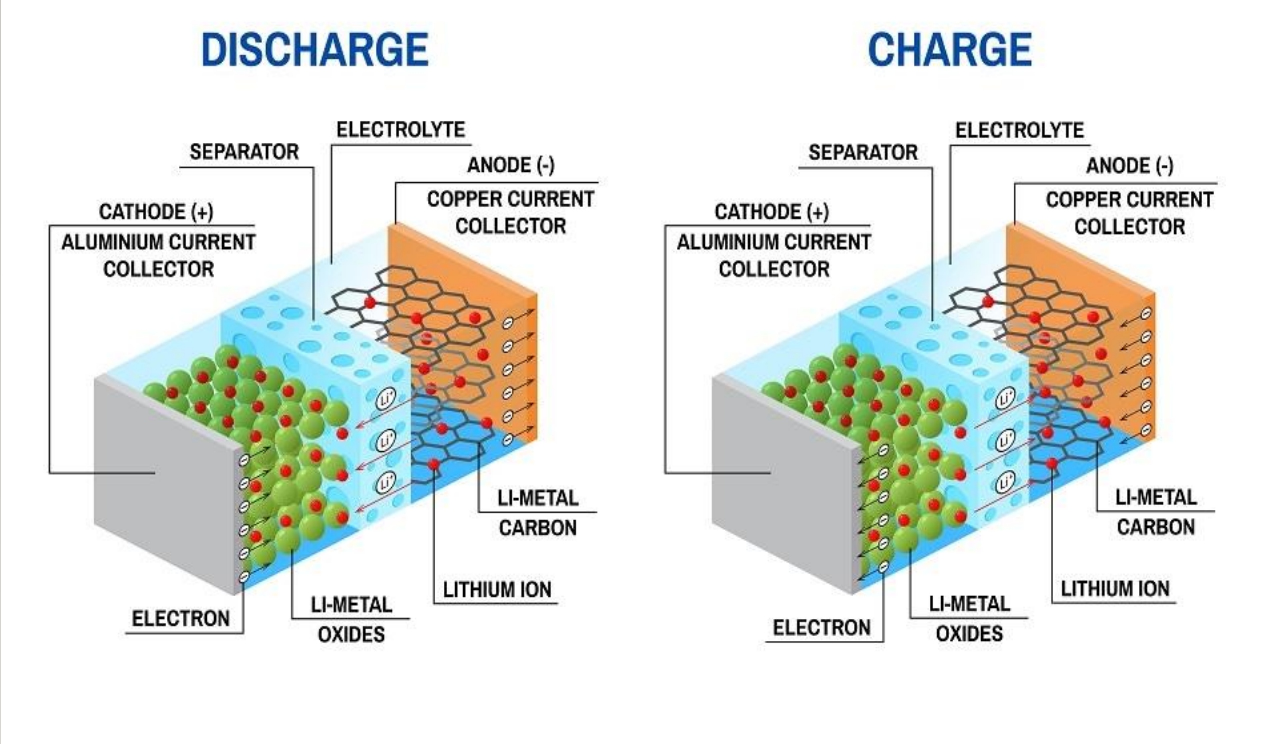
SODIUM-SULPHUR BATTERY



Sodium–sulphur battery

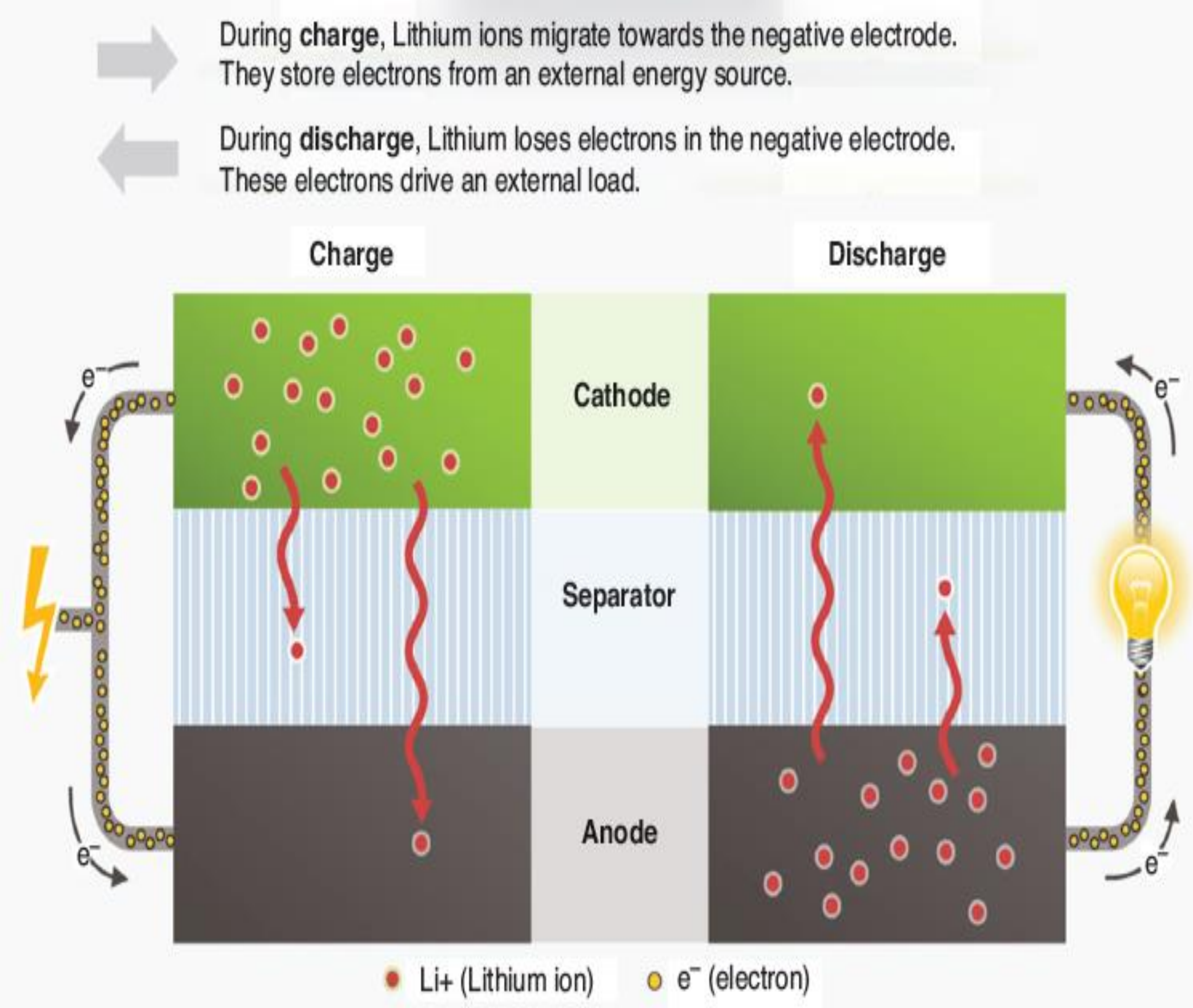
- **Each cell of this battery is very small, using 15 g of sodium.**
- **If cell is damaged, dangerous sodium to be converted into polysulphides, which are comparatively harmless.**
- **Small cells also have the advantage that they can be distributed around the car.**
- **Capacity of each cell is about 10 Ah with output voltage of 2 V.**

LI-ION BATTERY



- Dominant battery technology in BEVs & HEVs.
- Of all the metals lithium has the highest standard potential and electrochemical equivalent. Highest specific energy.
- Lithium is the lightest material.
- Energy density: 140-280 Wh/kg.
- Anode: LiC; Electrolyte: LiBr
- Cathode: Lithium Cobalt oxide
- Lithium-ions are deposited between these layers.

LI-ION BATTERY



- In cold conditions, lithium-ions' movement is slower during charging which tends to make them reach the electrons on the surface of the anode rather than inside it.
- Research is ongoing and one possible solution could be to warm up the battery before charging.

LI-ION BATTERY

Figure 5.16 Lithium-ion battery
(Source: Bosch Media)

BATTERY PLUG-IN & LIFE

- Main sources of lithium for EV batteries are salt lakes and salt pans, which produce soluble salt lithium chloride.

- Lithium can also be extracted from sea water.
- Worldwide reserves are estimated to be about 30 million tons.
- Main producers of lithium are South America (Chile & Argentina), Australia, Canada and China.
- Around 0.3 kg of lithium is required per kWh of battery storage.

BATTERY PLUG-IN & LIFE

- **End of life for a battery is considered when the battery capacity drops to 80% of rated capacity.**
- **If battery has a range of 100 km from a full charge, after 8–10 years of use the range may reduce to 80 km.**
- **However, batteries can still deliver usable power of 80% charge capacity.**
- **Recycling will become a major source of lithium.**
- **Lithium-ion cells are considered non-hazardous and they contain useful elements that can be recycled.**
- **Lithium, metals (copper, aluminium, steel), plastic, cobalt and lithium salts can all be recovered.**

CHARGING

- **Charging is process where the energy is being flow into the rechargeable battery by forcing an electrical current through it.**

Figure 7.4 Domestic charging point

Road side Charging Point

CHARGING TIME

Key Fact

Charge time for an EV depends on the type of vehicle, how discharged the battery is and the type of charge point used.

- **Pure-EVs capable of using rapid charge points & fully charged in 30 min, topped up in 20 minutes, depending on type of charge point and available power.**
- **PHEVs take approx. 2 hr to charge from a standard electricity supply.**

Table 7.1 Estimated charging times

Charging time for 100-km range	Power supply	Power	Voltage	Max. current
6–8 hours	Single phase	3.3 kW	230 V AC	16 A
3–4 hours	Single phase	7.4 kW	230 V AC	32 A
2–3 hours	Three phase	10 kW	400 V AC	16 A
1–2 hours	Three phase	22 kW	400 V AC	32 A
20–30 minutes	Three phase	43 kW	400 V AC	63 A
20–30 minutes	Direct current	50 kW	400–500 V DC	100–125 A
10 minutes	Direct current	120 kW	300–500 V DC	300–350 A

CHARGING COST

- **Cost of charging an EV depends on the size of the battery and how much charge is left in the battery before charging.**

- **Charging an electric car from flat to full will cost from £1 to £4 for 24 kWh battery/100-mile range.**
- **Overnight charging is advantageous @ cheaper rate when there is surplus energy.**
- **Cost of charging from public points will vary.**

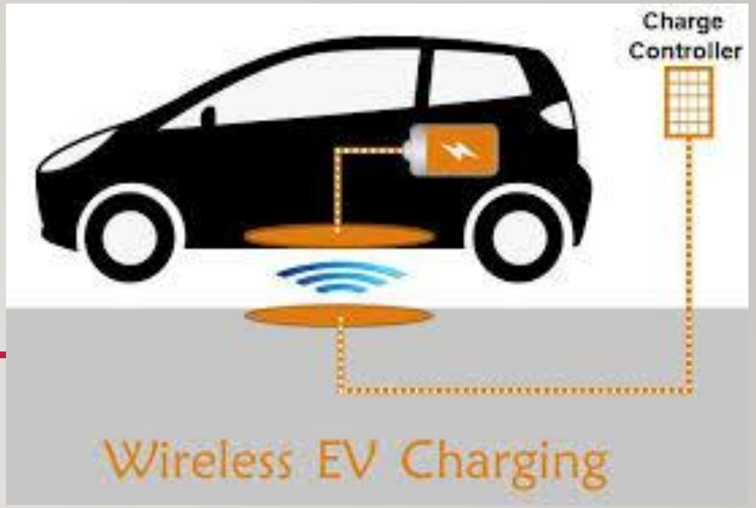
CHARGING STANDARDS

Necessary to standardize charging cables, sockets and methods. IEC publishes the standards that are valid worldwide.

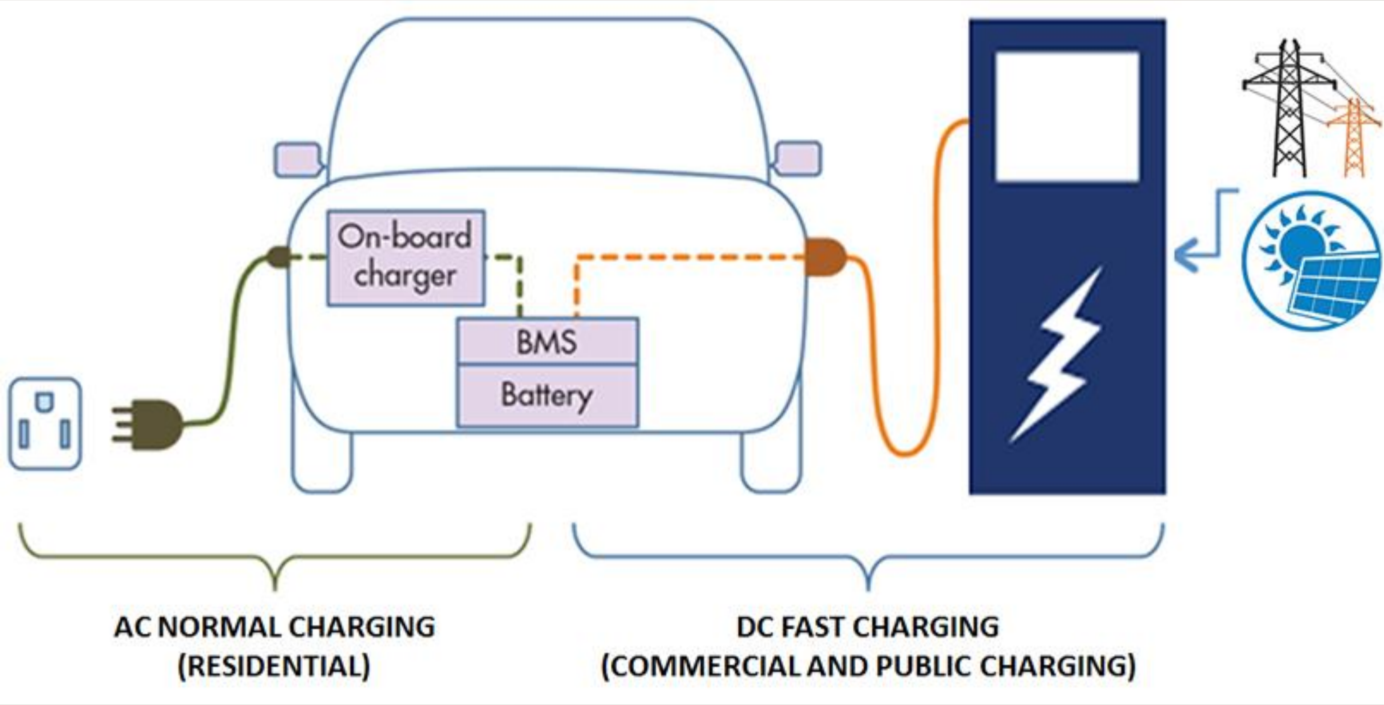
Table 7.2 Charging standards

IEC 62196-1	IEC 62196-2	IEC 62196-3	IEC 61851-1	IEC 61851-21-1	IEC 61851-21-2	HD 60364-7-722
Plugs, socket-outlets, vehicle connectors and vehicle inlets. Conductive charging of electric vehicles	Dimensional compatibility and interchangeability requirements for AC pin and contact tube accessories. The permissible plug and socket types are described	Dimensional compatibility and interchangeability requirements for dedicated DC and combined AC/DC pin and contact-tube vehicle couplers	Electric vehicle conductive charging system. Different variants of the connection configuration, as well as the basic communication with the vehicle, are defined in this standard	Electric vehicle conductive charging systems. Electric vehicle on-board charger EMC requirements for conductive connection to an AC/DC supply	Electric vehicle conductive charging systems EMC requirements for off-board electric vehicle charging systems	Low-voltage electrical installations. Requirements for special installations supply of electric vehicles

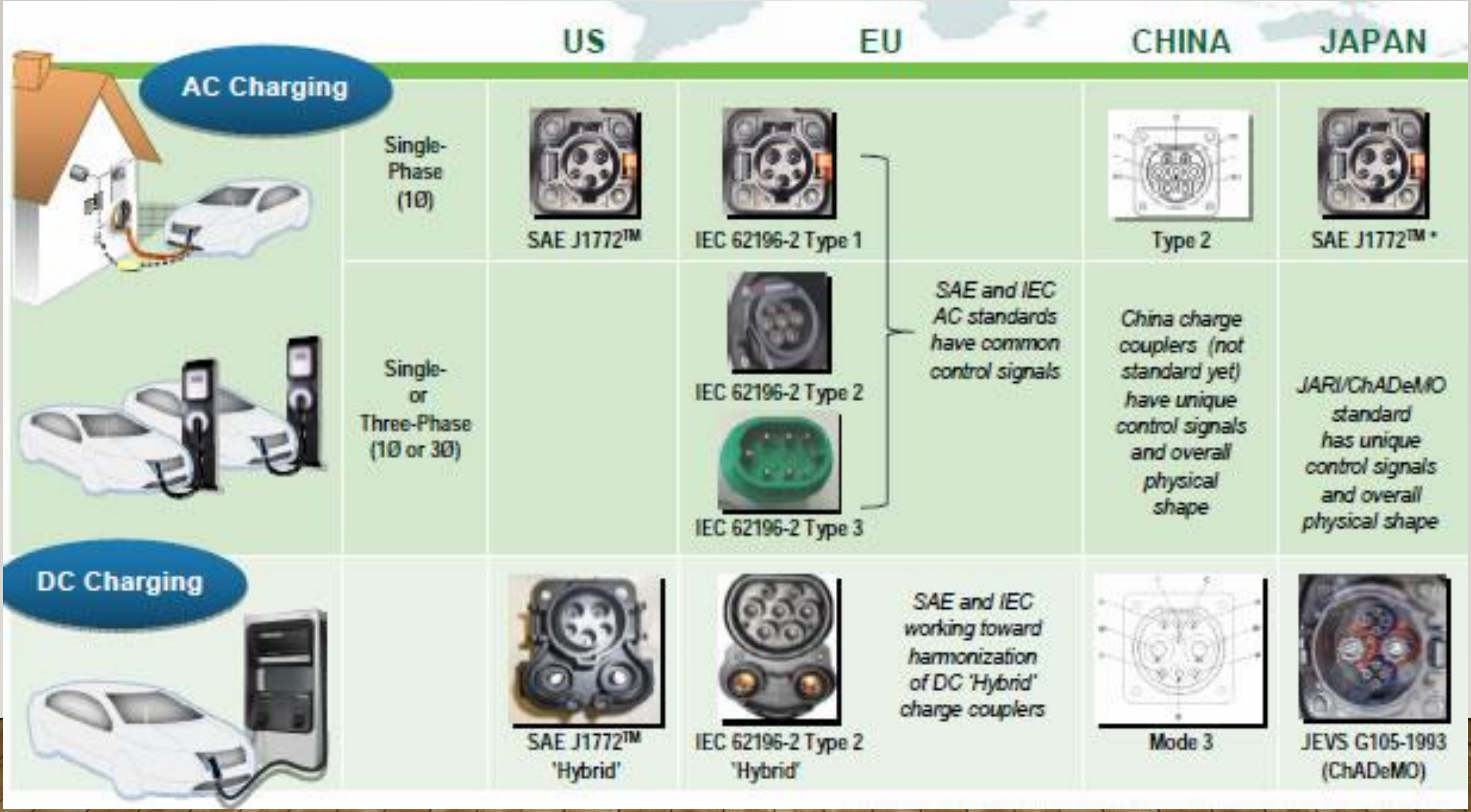
CHARGING METHODS



- AC Charging
- DC Charging
- Inductive Charging



AC CHARGING


US
EU
CHINA
JAPAN
AC Charging
Single-Phase (1Ø)
SAE J1772™
IEC 62196-2 Type 1
Type 2
SAE J1772™ *
Single- or Three-Phase (1Ø or 3Ø)
IEC 62196-2 Type 2
IEC 62196-2 Type 3
SAE and IEC AC standards have common control signals
China charge couplers (not standard yet) have unique control signals and overall physical shape
JARI/ChADeMO standard has unique control signals and overall physical shape
DC Charging
SAE J1772™ 'Hybrid'
IEC 62196-2 Type 2 'Hybrid'
SAE and IEC working toward harmonization of DC 'Hybrid' charge couplers
Mode 3
JEVS G105-1993 (ChADeMO)

AC CHARGING

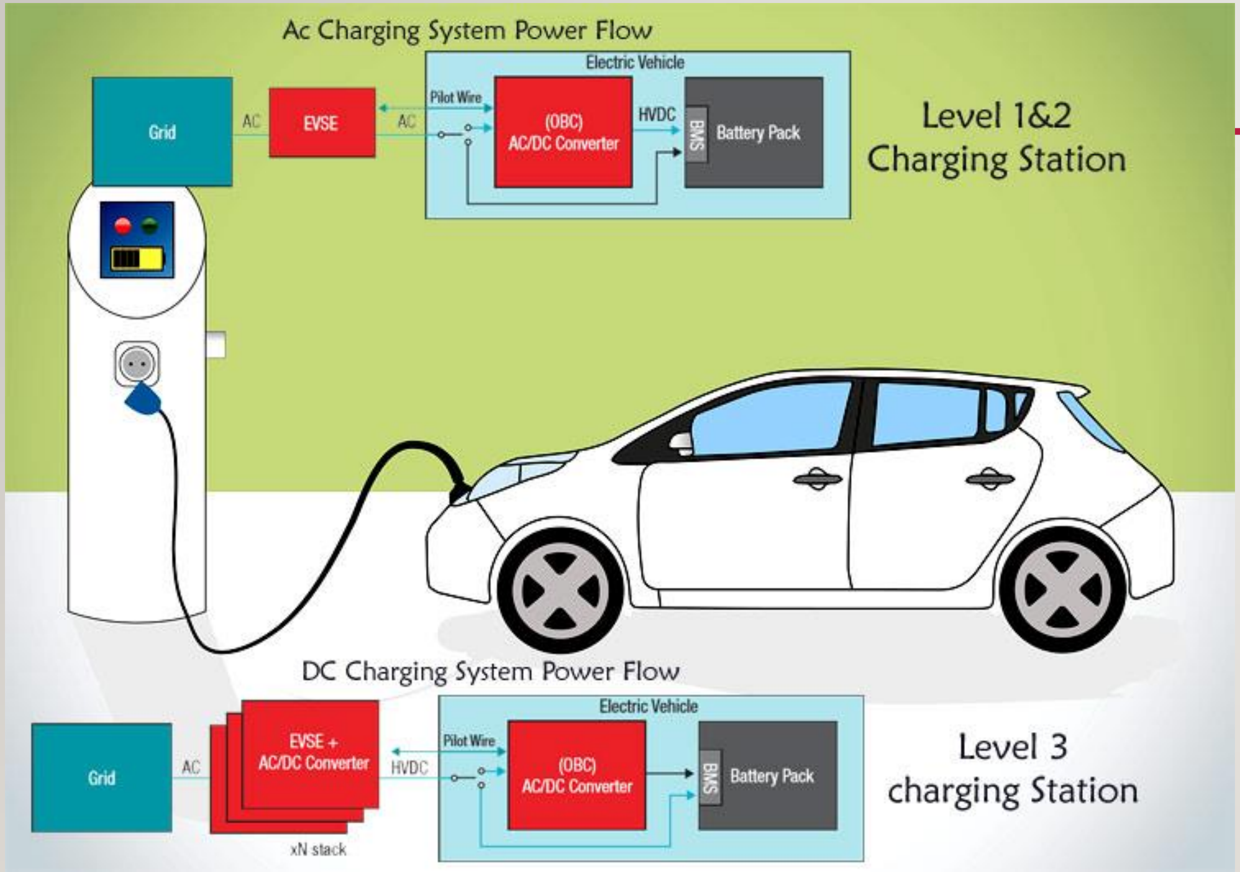
- Established as standard charging method.
- Charging occurs via an AC connection.
- Most common and flexible charging method.

- Possible in private sector/charging stations in semi-public and public sector, with low investments.
- In charging modes 1 and 2, charging is possible on household sockets.
- On the household socket, charging can take up to several hours due to the power limited through the socket.

AC CHARGING

- In charging mode 3 a vehicle can be charged at a charging station where power of up to 43.5 kW is possible with a significantly reduced charging time.
- Charging device is permanently installed in the vehicle. Its capacity is adjusted to the vehicle battery.
- Compared with other charging methods, investment costs are moderate.

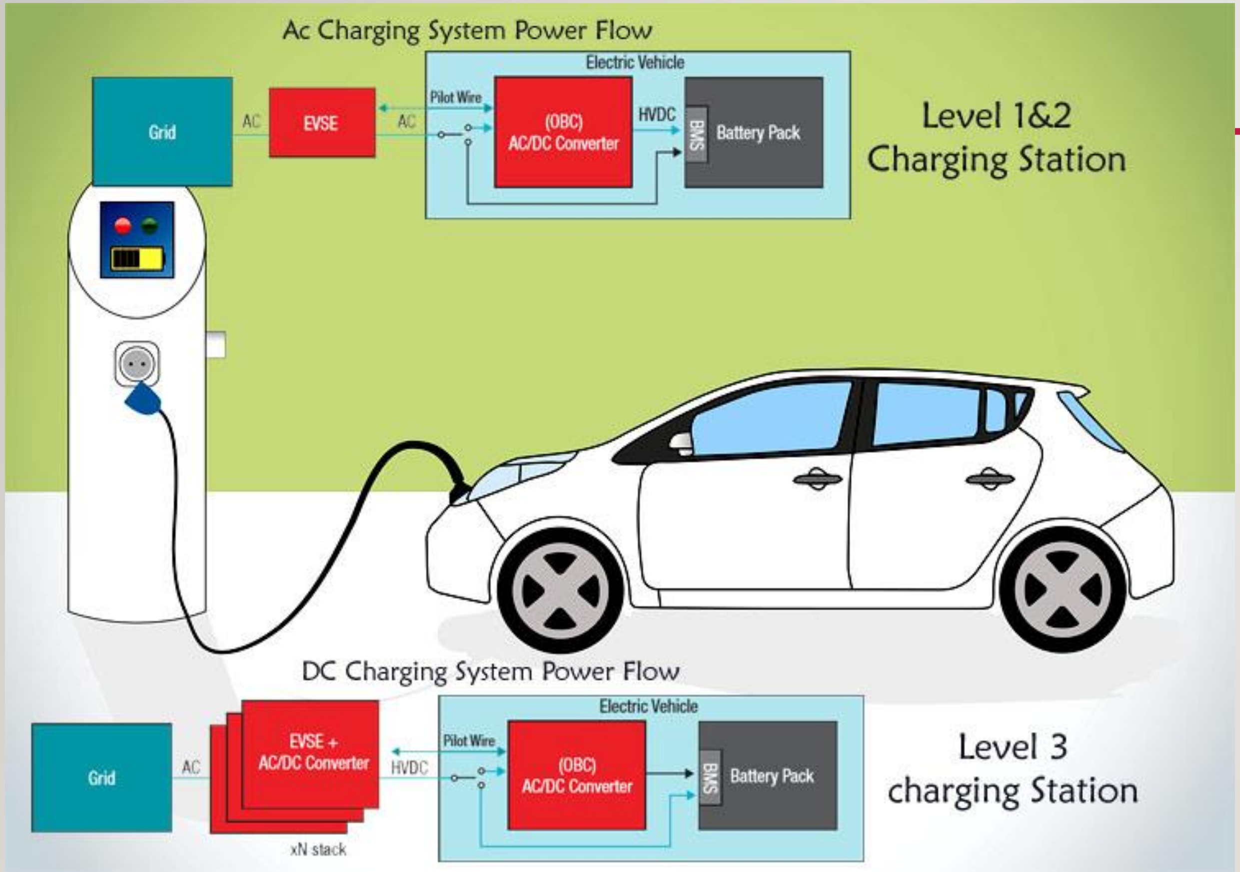
DC CHARGING



- **DC low charging: up to 38 kW.**
- **DC high charging: up to 170 kW.**

- **Charging device is part of charging station.**
- **Expensive as compared with AC charging stations.**
- **Prerequisite: Appropriate network of charging stations, which due to the high power require high infrastructure investments.**

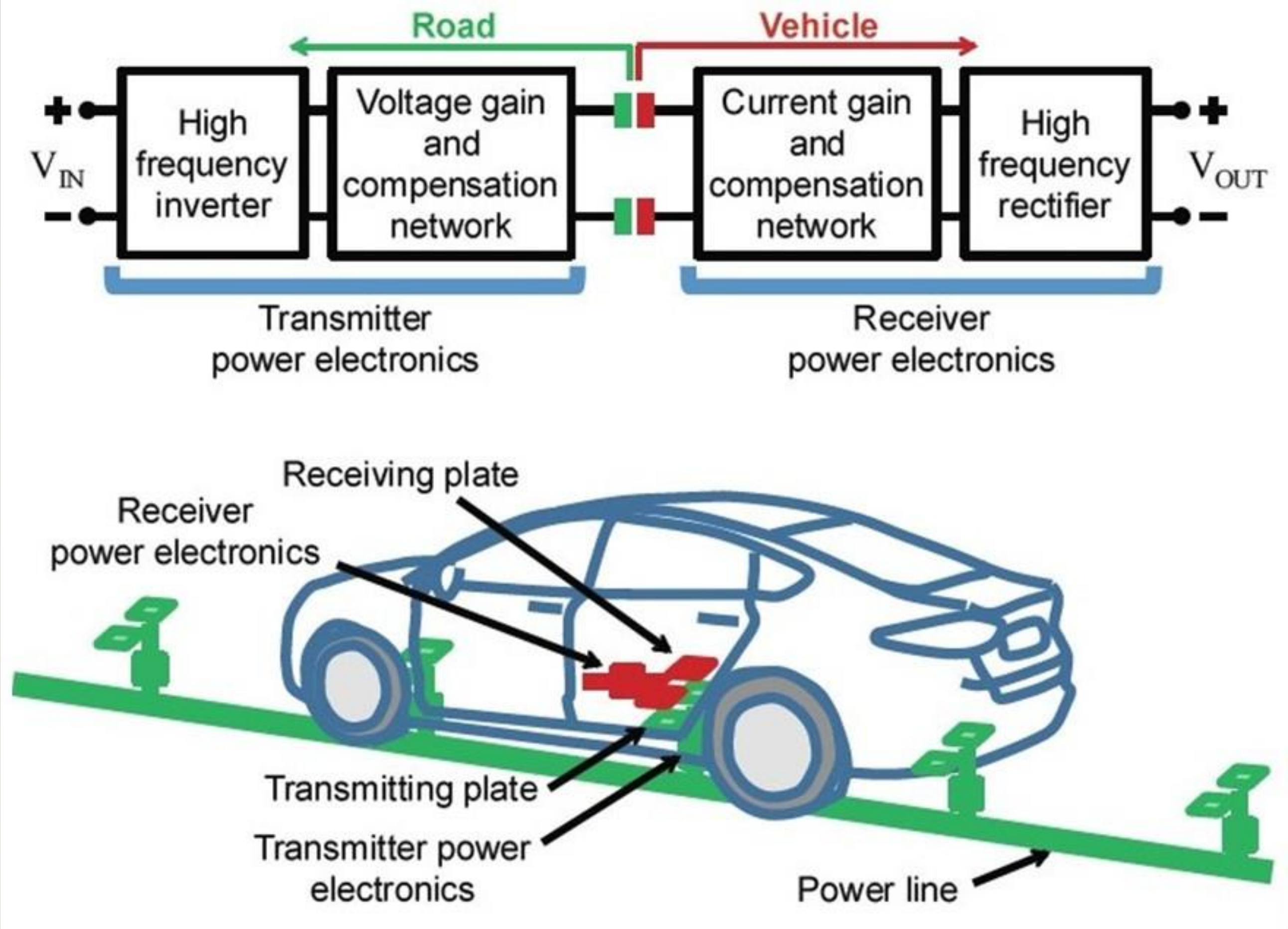
DC CHARGING



- **Standardization of DC charging connection has not yet been concluded and market availability is still uncertain.**

- **In practice, vehicles with a DC charging connection have an additional connection for standard charging so that the vehicle can also be charged at home.**

INDUCTIVE CHARGING



- **Type of short distance wireless charging.**
- **No physical contact between transmission & receiving end.**
- **Works on the Principle of Electromagnetic Induction.**
- **Charger will create an EM field with alternating polarity using a coil of insulated wire of copper & similar coil will be placed inside E-Vehicle will convert EM field back to the electric current thereby charging the battery.**

Different Modes of charging-

Mode-1

- AC Charging
- Regular household outlet
- Un-safe - Not recommended to use

Mode-2

- AC Charging
- In-cable control and protection (IC-CPD)
- Limited to 3.7kW (16A) in residential use or 7.4kW (32A) for industrial

Mode-3

- AC charging
- Control, communications and protection functions incorporated in the charge point (EVSE)
- Wide range of charging : 3.7KW to 43KW

Mode-4

- DC charging
- Option of either CHAdeMO or CCS
- For public and commercial charging applications
- Wide range of charging capabilities – over 150kW

CHARGING MODES

WIRELESS CHARGING (OR) WIRELESS POWER TRANSFER - WPT

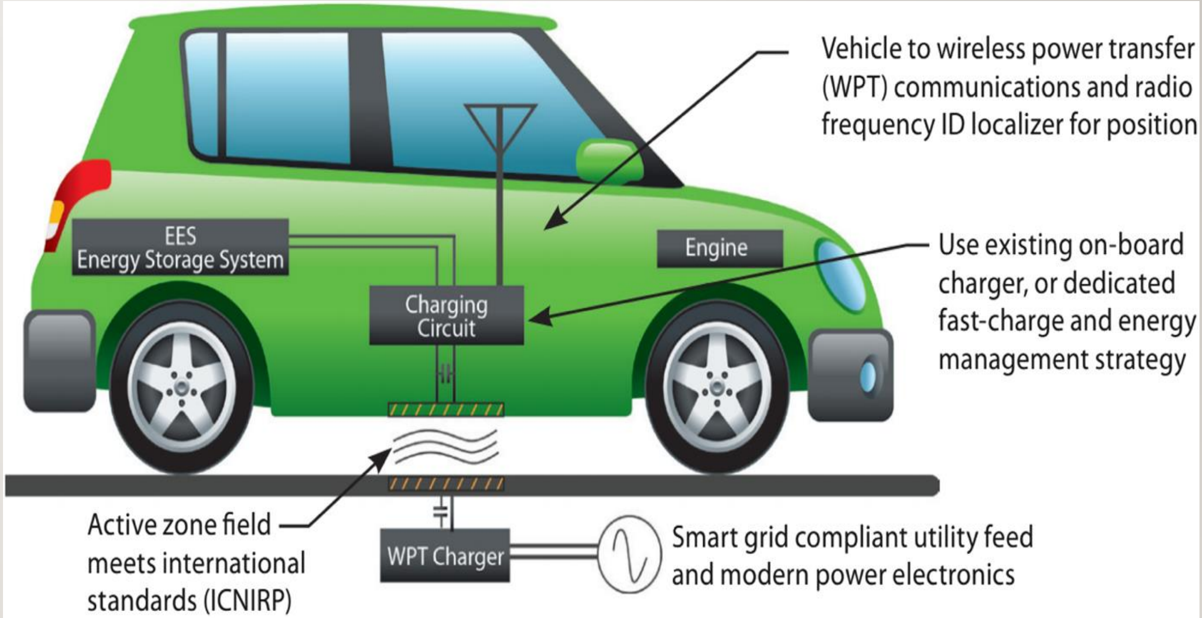
- WPT is an innovative system for charging the batteries in electric vehicles.

Types

- Static WPT: vehicle is parked, no driver is in vehicle
- Quasi-dynamic WPT: vehicle stopped, driver is in the vehicle
- Dynamic WPT: vehicle is in motion.
- Also three WPT power classes (SAE J2954):
- Light Duty Home: 3.6 kW
- Light Duty Fast Charge: 19.2 kW
- High Duty: 200–250 kW.

STATIC - WPT

- **With stationary charging, the electric energy is transferred to a parked vehicle (without passengers on board).**
- **Electric vehicles simply park over an induction pad and charging commences automatically.**
- **WPT requires no charging poles or associated cabling only requires a charging pad buried in the pavement and a pad integrated onto the vehicle.**



STATIC - WPT

- **Consists of a primary power supply with track and a secondary pick-up pad & controller.**
- **Electrical power from mains and energizes a lumped coil, with a current in the range 5–125 A.**
- **As coil is inductive, compensation using series or parallel capacitors may be required to reduce the working voltages and currents in the supply.**
- **Pick-up coils are magnetically coupled to primary coil.**
- **Power transfer is achieved by tuning the pick-up coil to the operating frequency of the primary coil with a series or parallel capacitor.**
- **Power transfer is controllable with a switch-mode controller.**

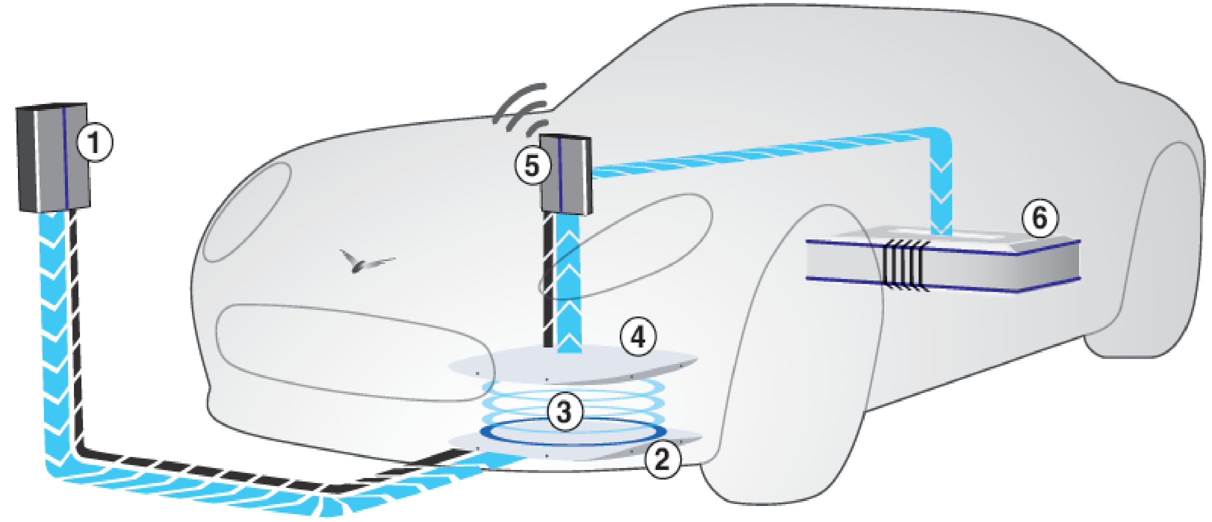


Figure 7.19 An inductive wireless charging system for statically charging an EV: 1, power supply; 2, transmitter pad; 3, wireless electricity and data transfer; 4, receiver pad; 5, system controller; 6, battery (Source: haloIPT)

DYNAMIC- WPT

- **Driver assistance systems may play a role.**
- **With stationary wireless charging, a system could be developed where the vehicle is parked automatically and at the same time primary and secondary coils are brought into perfect alignment.**
- **With quasi-dynamic and dynamic charging the vehicle speed as well as horizontal and vertical alignment could be automatically adapted by dynamic cruise control and lane assist.**
- **This would increase the efficiency rate of the energy transfer.**

ULTRA CAPACITOR

- Known as Double-layer capacitor or Super capacitor.

- **Ultracapacitors are energy storage devices offering high power and high energy simultaneously, compared with conventional capacitors and batteries.**

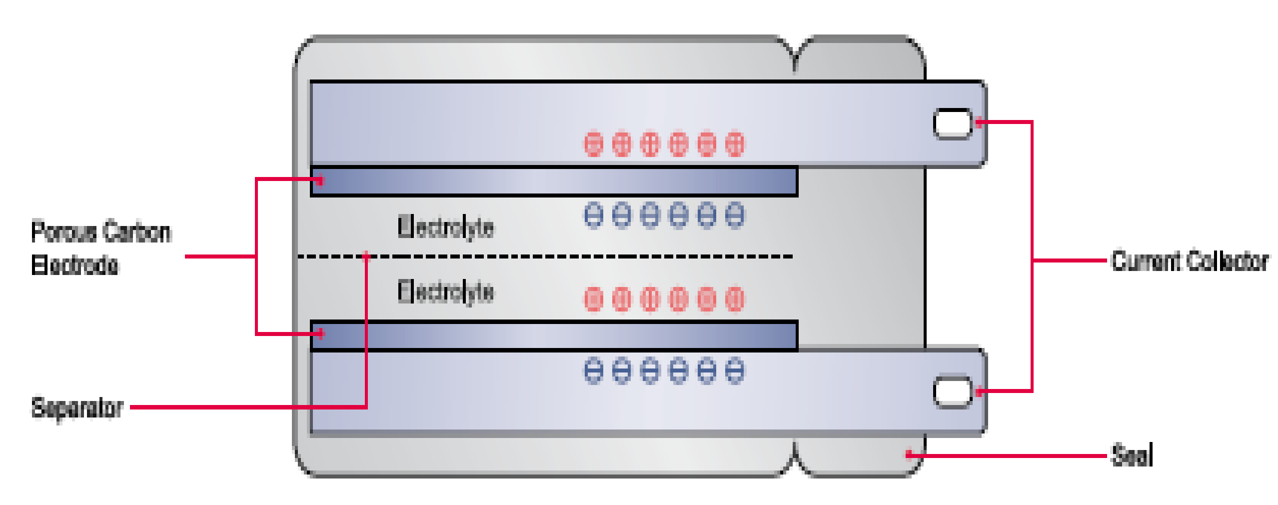
- **High power, long shelf and cycle life performance of Ultracapacitors originate in the energy storage mechanism differing from batteries.**

- With batteries, energy is stored and released via chemical reaction that causes degradation of the entire system.

- Ultracapacitors use physical charge separation phenomena between the charge on an electrode and ions in electrolyte at the interface.

- Since the charge and discharge processes are purely physical and highly reversible, Ultracapacitors can release energy much faster and with more power compared to batteries.

- Can be cycled hundreds of thousands of times without significant effect on performance.

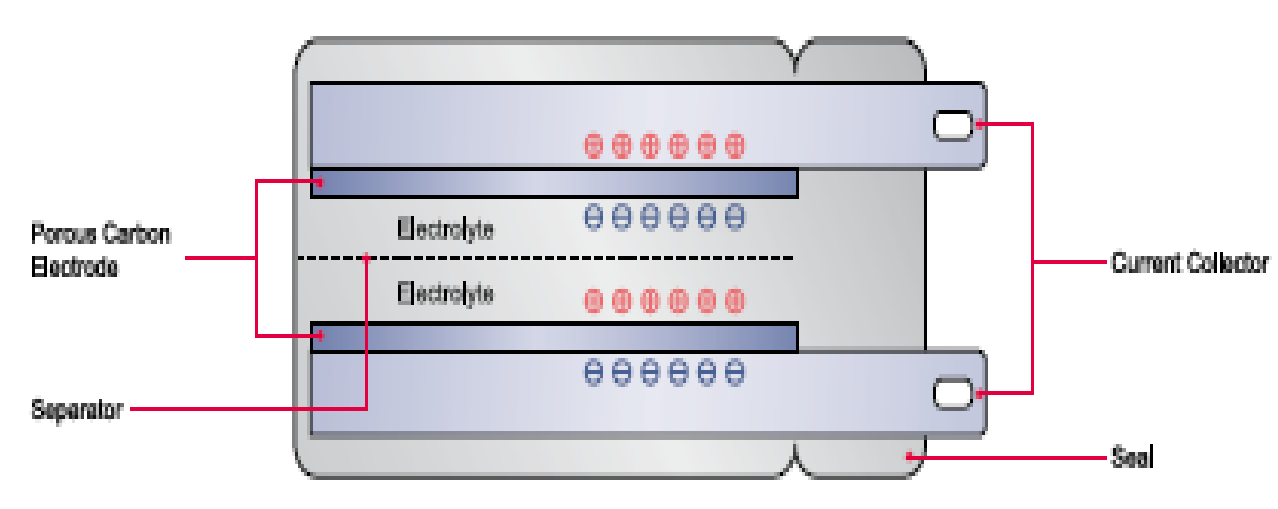


ULTRA CAPACITOR

ULTRA CAPACITOR

- Ultracapacitors also have two metal plates, coated with a sponge-like, porous material known as activated carbon immersed in an electrolyte made of positive and negative ions dissolved in a solvent.

- One carbon-coated plate, or electrode, is positive, and the other is negative. During charging, ions from the electrolyte accumulate on the surface of each carbon-coated plate.



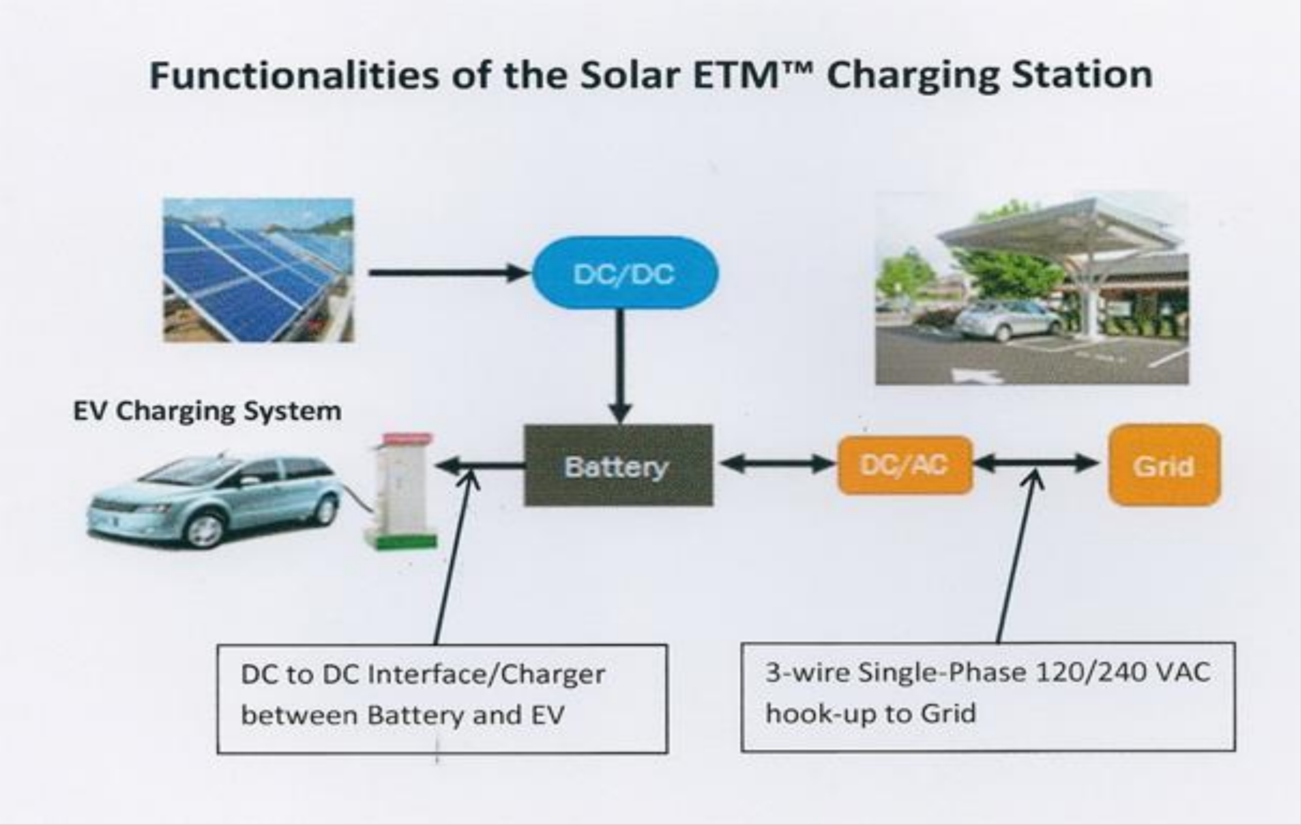
Strengths and Weaknesses of Ultracapacitors

Strong Attributes of Ultracapacitors	Potential Specific Use
High specific power and efficiency	Engine assist
Efficient and fast charge acceptance	Regen capture
Low resistance	Lower cooling needs (less expensive)
Quick response (short time constant)	Supporting engine transients
Long anticipated calendar and cycle life	Fewer replacements (less expensive)
High specific power at low temperatures (cold starts)	Smaller size and less expensive

Weak Attributes of Ultracapacitors	Specific Use
Low specific energy	Limited "durations" for power draw
High self-discharge	Loss of functionality and balance at start
Quick voltage variation	More difficult to control
Low energy density	Limited time for running auxiliaries at idle
High cost per unit energy	Too expensive currently

The best use for Ucaps are strategies that make engines operate more efficiently (idle off, load leveling), frequent use capturing regen energy, and start-stop.

CHARGING E-VEHICLE USING SOLAR POWER



CAPACITORS

- A capacitor is used to store and release electrical energy. Capacitors can be used to smooth out current fluctuations, store and release a high voltage, or block DC voltage.
- Although a battery and a capacitor store electrical energy, the battery stores the energy chemically.
- A capacitor stores energy in an electrostatic field created between a pair of electrodes.

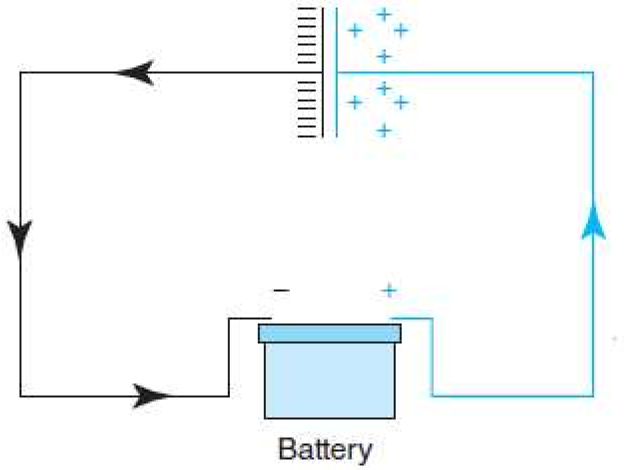


Figure 4-34 A capacitor stores energy in an electrostatic field created between a pair of electrodes.

- A capacitor can release all of its charged energy in an instant, whereas a battery slowly releases its charge. A capacitor is quick to discharge and quick to charge.
- A battery needs some time to discharge and charge, but it can provide continuous power.
- A capacitor only provides power in bursts.

- Capacitors have a positive and a negative terminal. Each terminal is connected to a thin electrode or plate (usually made of metal).
- The plates are placed in parallel to each other and are separated by a dielectric.
- The dielectric can be paper, plastic, glass, or anything that does not conduct electricity. Placing a dielectric between the plates allows the plates to be close to each other without allowing them to touch.
- When voltage is applied to a capacitor, the two electrodes receive equal but opposite charges.
- The plate in the capacitor that is connected to the negative terminal of the battery, or other power source, accepts electrons and stores them on its surface.
- The other plate loses electrons to the power source. This action charges the capacitor.
- Once the capacitor is charged, it has the same voltage as the power source.

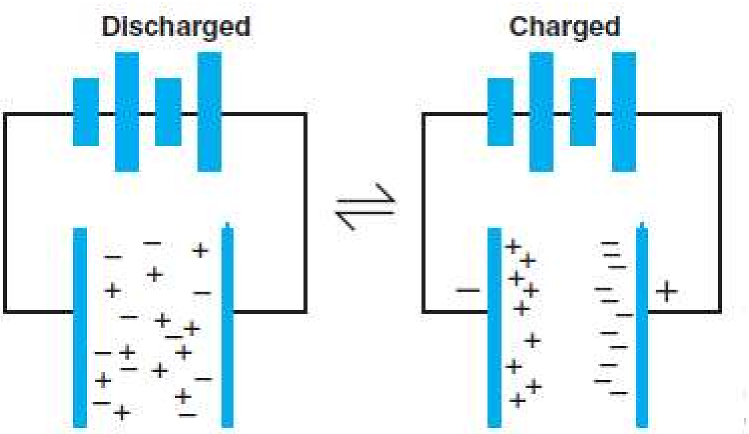


Figure 4-35 When voltage is applied to a capacitor, the two electrodes receive equal but opposite charges.

- This energy is stored until the two terminals are connected together. The ability of a capacitor to store an electric charge is called capacitance.
- The standard measure of capacitance is the farad (F).
- Most capacitors have a capacitance

rating of much less than a farad, and their values are

given as:

- microfarads: μF (1 μF = 10^{-6} F)
- nanofarads: nF (1 nF = 10^{-9} F)
- picofarads: pF (1 pF = 10^{-12} F)

- Three major factors determine the capacitance of a capacitor: the insulating qualities of the dielectric, the surface area of the electrodes, and the distance between the electrodes.

- The amount of capacitance is directly proportional to the surface areas of the plates and the non conductiveness of the dielectric, and is inversely proportional to the distance between the plates.
- Capacitors have a major role in today’s electric drive vehicles. They are used to protect the high-voltage battery from unwanted voltage spikes that could damage the battery.
- Some vehicles have a ‘‘backup control’’ 12 volts just in case the regenerative braking stops working.
- The backup unit allows the electrically controlled brake system to operate long enough to stop the vehicle.
- When the capacitors in the backup control are totally discharged, the brake system reverts to a completely hydraulic system.

ULTRA-CAPACITORS

- An ultra-capacitor is not a battery; however, it can function much like one. This device stores and releases electrical energy electrostatically, rather than electrochemically.
- Ultra-capacitors have the ability to quickly discharge high voltages and then be quickly recharged. These characteristics make them ideal for adding electrical energy to motors when a vehicle needs extra power for acceleration or to overcome heavy loads.

- Ultra-capacitors are also very good at absorbing the energy from regenerative braking.
- Some current hybrid vehicles use ultra-capacitors for both purposes.
- Ultra (or super)-capacitors are capacitors with a large electrode surface area and a very small distance between the electrodes. These features give them very high capacitance, which is why they are called ultra- or super-capacitors. Some ultra-capacitors are rated at 5,000 farads.
- Ultra-capacitors use an electrolyte rather than a dielectric and store electrical energy at the boundary between the electrodes and the electrolyte.
- Although an ultra-capacitor is an electrochemical device, no chemical reactions are involved in the storing of electrical energy.
- As a result, they have no negative impact on the environment.
- Ultra-capacitors are maintenance-free devices. They can withstand an infinite number of charge/discharge cycles without degrading and have a long service life.
- They also are very good at capturing the large amounts of energy from regenerative braking, and they can deliver power for acceleration and heavy loads quickly.

- Also, because they charge very quickly, they have energy available shortly after they have been discharged.
- Ultra-capacitors, however, cannot store as much total energy as batteries and they are expensive to manufacture.
- To provide the required high voltages for electric vehicles, several capacitors must be connected in series.
- Each cell of an ultra-capacitor can only store between 2 and 5 volts. Up to 500 cells are required to meet the needs of a typical electric drive vehicle.

Construction.

- A regular capacitor is made of conductive foils and a dry separator.
- An ultra-capacitor has two special electrodes and some electrolyte, much like a battery cell.

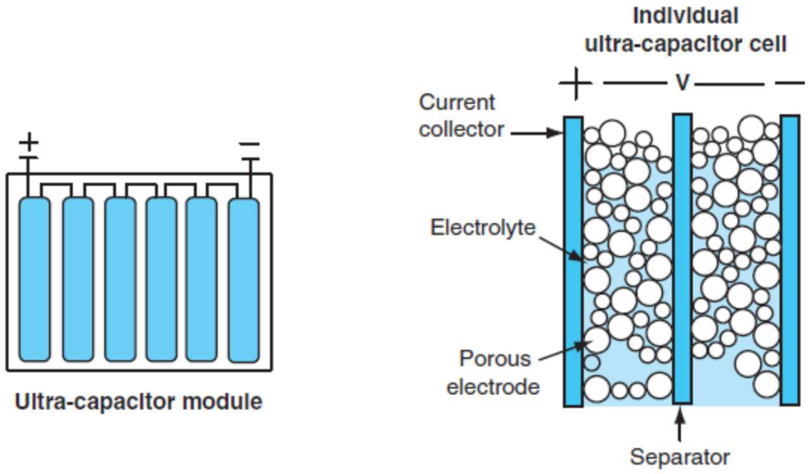


Figure 4-36 An ultra-capacitor cell.

- The electrodes are typically made of carbon but can be made from a metal oxide or conducting polymers.
- The carbon surface of the electrodes is very coarse, with thousands of microscopic peaks and valleys. These irregularities increase the electrodes' surface area.
- In fact, an ounce (28.35 grams) of carbon provides nearly 13,500 square feet (1,250 sq. m) of surface area.
- The plates are immersed in an electrolyte. The electrolyte is typically boric acid or sodium borate mixed in water and ethylene glycol to reduce the chances of evaporation.
- When voltage is applied across the capacitor, the electrolyte becomes polarized.
- The charge of the positive electrode attracts the negative ions in the electrolyte and the charge of the negative electrode attracts the positive ions.
- When the positively charged ions form a layer on the surface of the negative electrode, electrons within the electrode, but beneath the surface, move to match up with them.
- The same occurs on the positive electrode, and these two layers of separated charges form a strong static charge.

- A porous, dielectric separator is placed between the two electrodes to prevent the charges from moving between them.
- This separator is ultra-thin; in fact, it is about half the size of the ions in the electrolyte. This small separator and the immense amount of surface area is what allow an ultra-capacitor to have high capacitance.

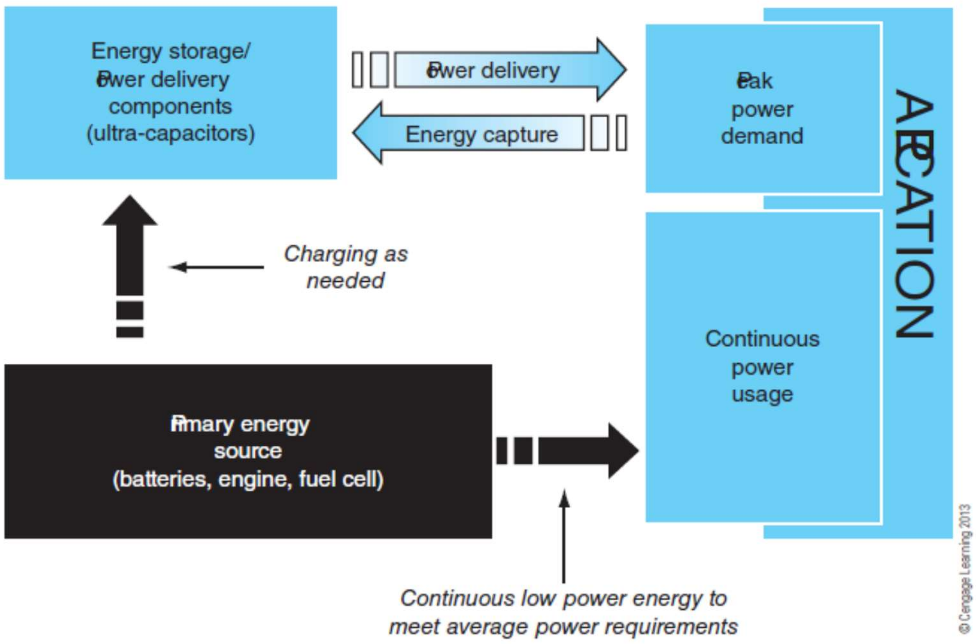


Figure 4-37 A diagram showing how an ultra-capacitor fits into the powertrain of a hybrid vehicle.

- However, the thin insulator is also the reason cell voltage must be kept low. High voltages would easily cause arcing across the plates.

Applications.

- The capacitors can store energy captured during deceleration and braking and can release that energy to the traction motor while it is assisting the engine during acceleration (Figure 4-37).

- Toyota Prius was the first automobile to use a bank of large capacitors. In a Prius, the energy in the capacitors is used to start the inverter immediately after a stop/start sequence.
- The capacitors also prevent current fluctuations to the inverter. Other full hybrid vehicles also have ultra-capacitors in their power platform.
- Mild hybrids, those with regenerative braking, a starter/generator, and the stop/start feature, can also benefit from the use of ultra-capacitors.
- These systems are 42-volt systems. In city driving when the vehicle stops, the engine shuts down. When it is time to accelerate, the engine starts again.
- In very heavy traffic, this of time. The cycling is very hard on batteries. An ultracapacitor can be used to provide the power needed to start the engine.
- Recharged by regenerative braking and/or the generator, the ultra-capacitor can be quickly charged and is capable of providing enough energy for two engine restarts after it is charged.
- Supplying only 42 volts, the ultra-capacitor pack is much less expensive than those required in a full hybrid.
- A bank of ultra-capacitors can also improve the performance of pure electric vehicles and fuel cell electric vehicles.

- Ultra-capacitors can allow a battery to be discharged and charged at a continuous rate. This would allow the use of simpler battery designs, ones that do not need to provide bursts of power or absorb bursts of energy from braking.

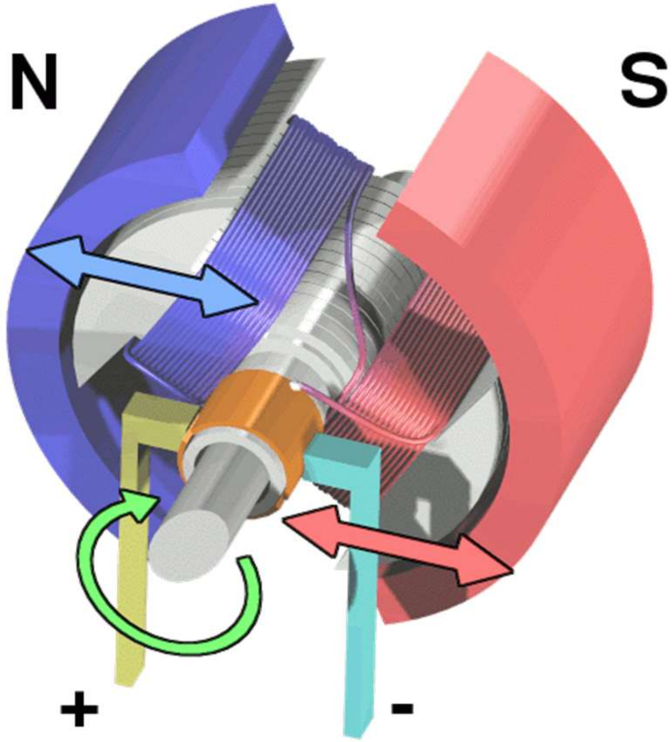
Charging.

- An ultra-capacitor is normally placed in parallel with a battery pack and is recharged by regenerative braking.
- An ultra-capacitor can also be charged with a battery charger. A typical ultra-capacitor needs about 10 seconds to be fully recharged.
- The charging process is much the same as that of a battery— the initial charge takes little time and current should be limited during the final stages of charging.
- The ultracapacitor is fully charged when it reaches the voltage as much energy as needed and, therefore, there is no possibility of overcharging.
- Once they are charged, they will not accept further charging. Ultra-capacitors can be recharged and discharged an unlimited number of times.

ELECTRIC VEHICLE MOTORS

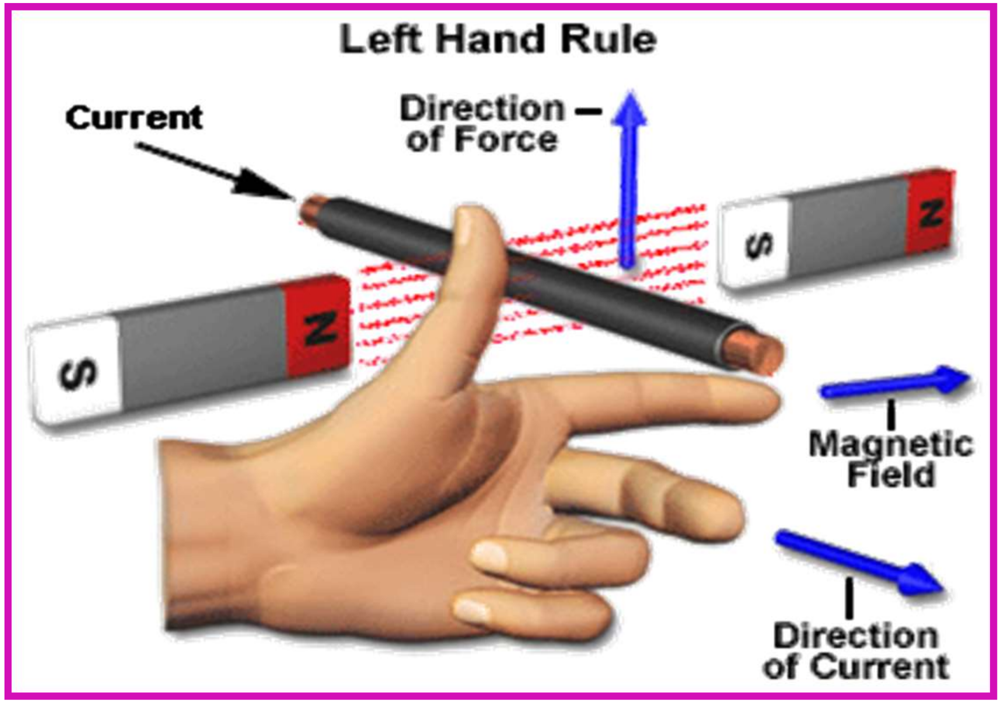
- Dc machines are of two types - DC generators & DC motors.
- A DC generators converts mechanical energy into electrical energy whereas a DC motor converts the electrical energy into mechanical energy.
- In order to understand operating principle of a DC motor, it is necessary to understand how does a current carrying conductor experience a force, when kept in a magnetic field.

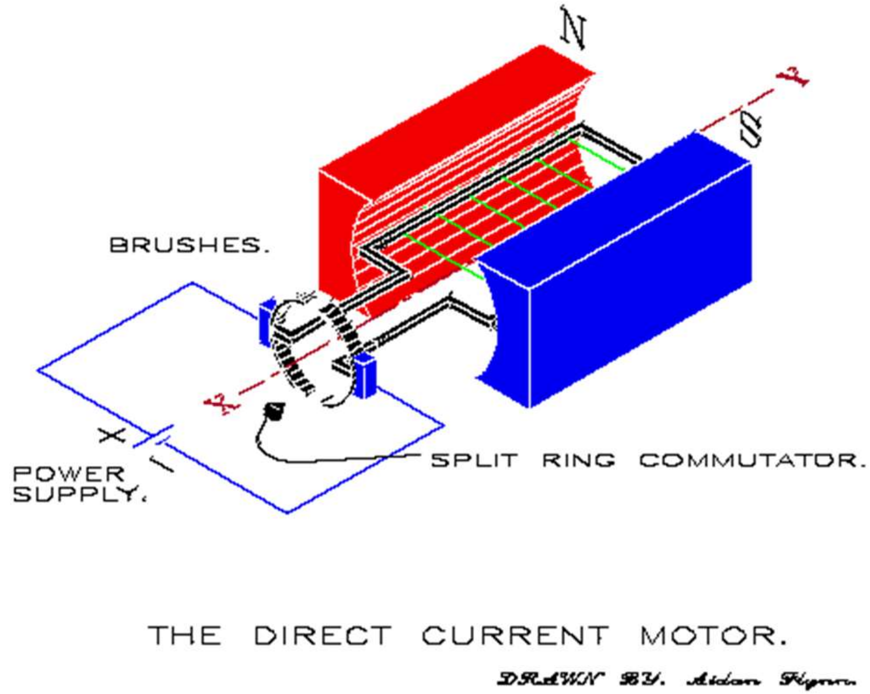
EV MOTOR – PRINCIPLE OF OPERATION



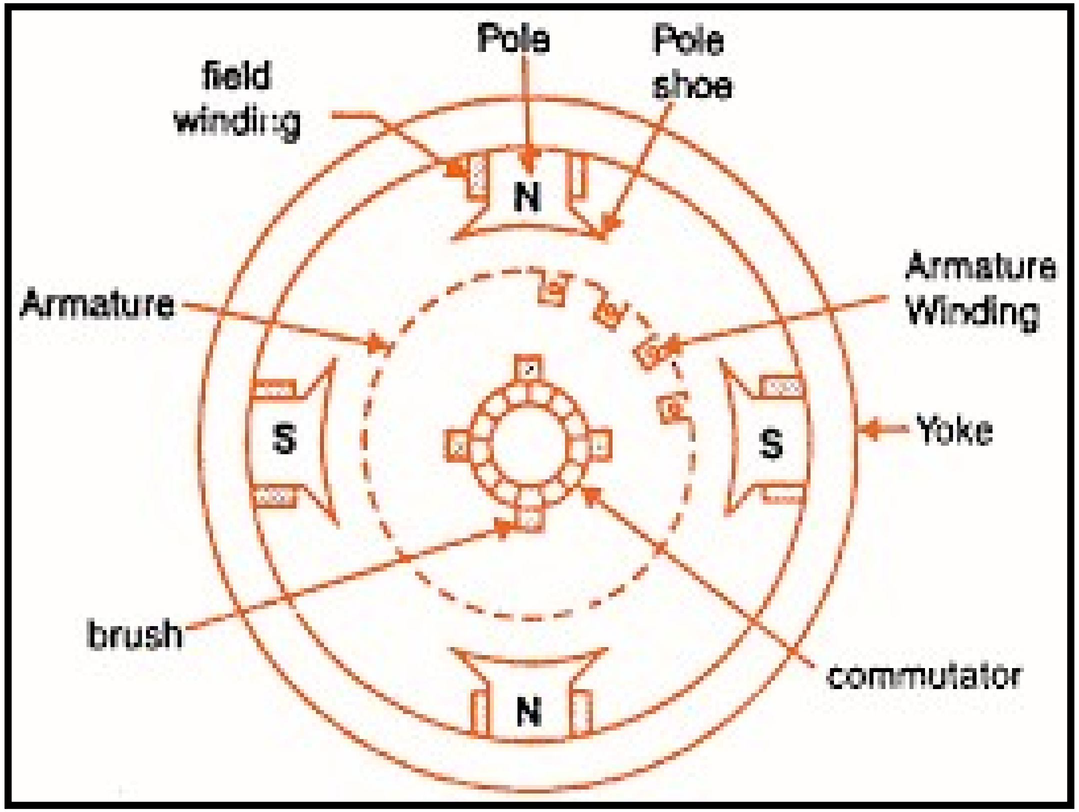
- When a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force.
- Direction is given by Flemings left hand rule
- Magnitude is F=B.I.L
- I=Current, L=conductor length, B=magnetic flux

EV MOTOR – PRINCIPLE OF OPERATION



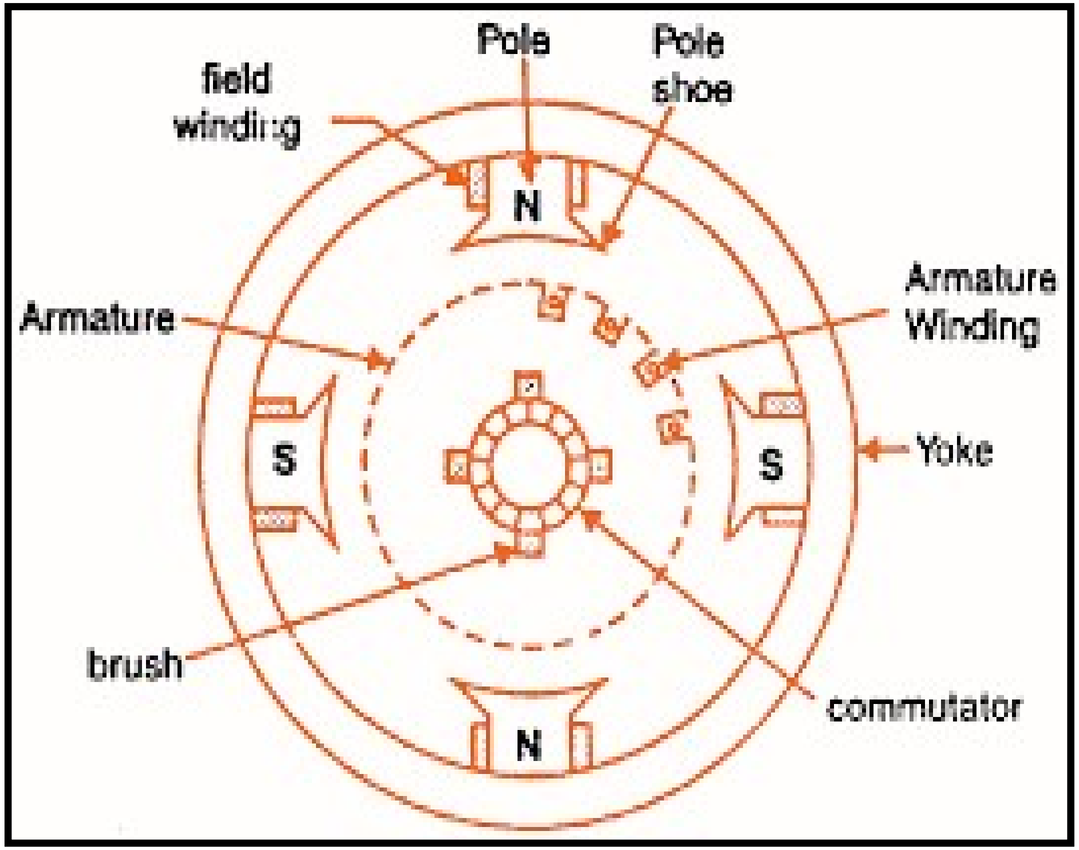


CONSTRUCTION OF DC MOTOR



- Yoke or Stator
- Field winding
- Poles
- Armature
- Commutator,
- Brushes & gear

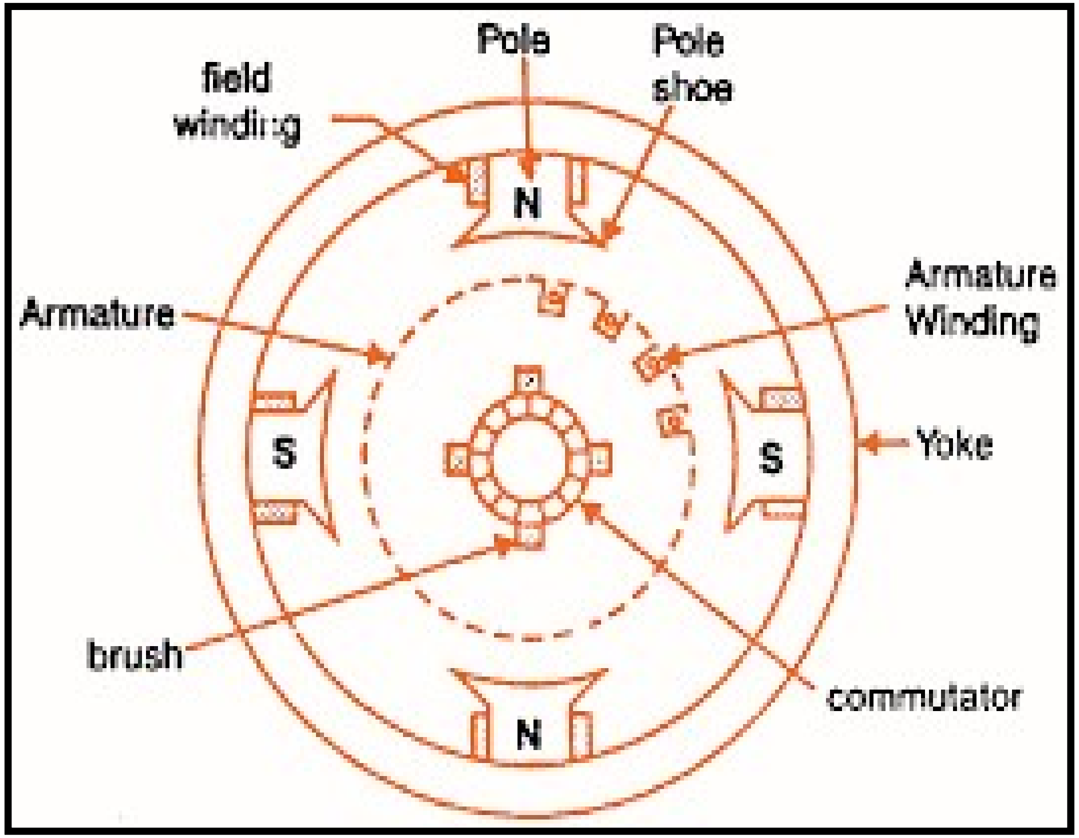
CONSTRUCTION OF DC MOTOR



YOKE or STATOR

- **Acts as outer support of a DC motor.**
- **Provides mechanical support for the poles.**

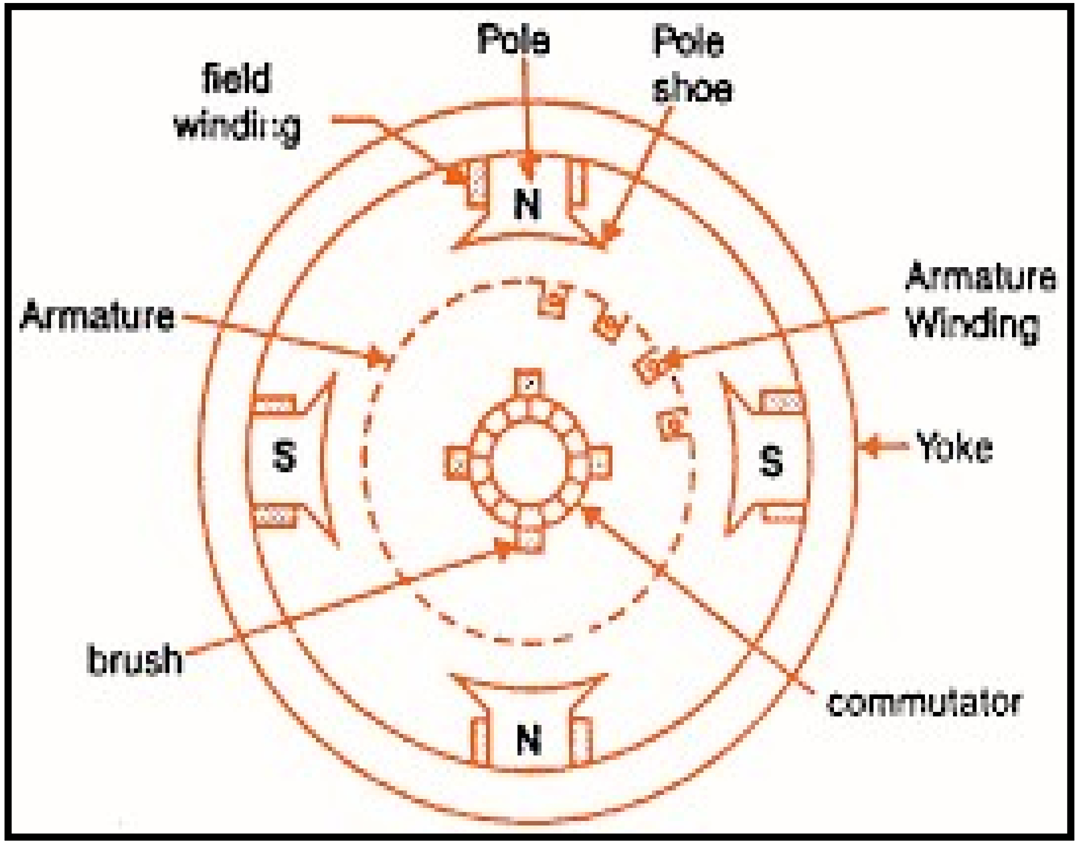
CONSTRUCTION OF DC MOTOR



FIELD WINDING

- Coils wound around the pole are called field coils and they are connected in series with each other to form field winding.
- When current passing through the field winding, magnetic flux produced in the air gap between pole and armature.

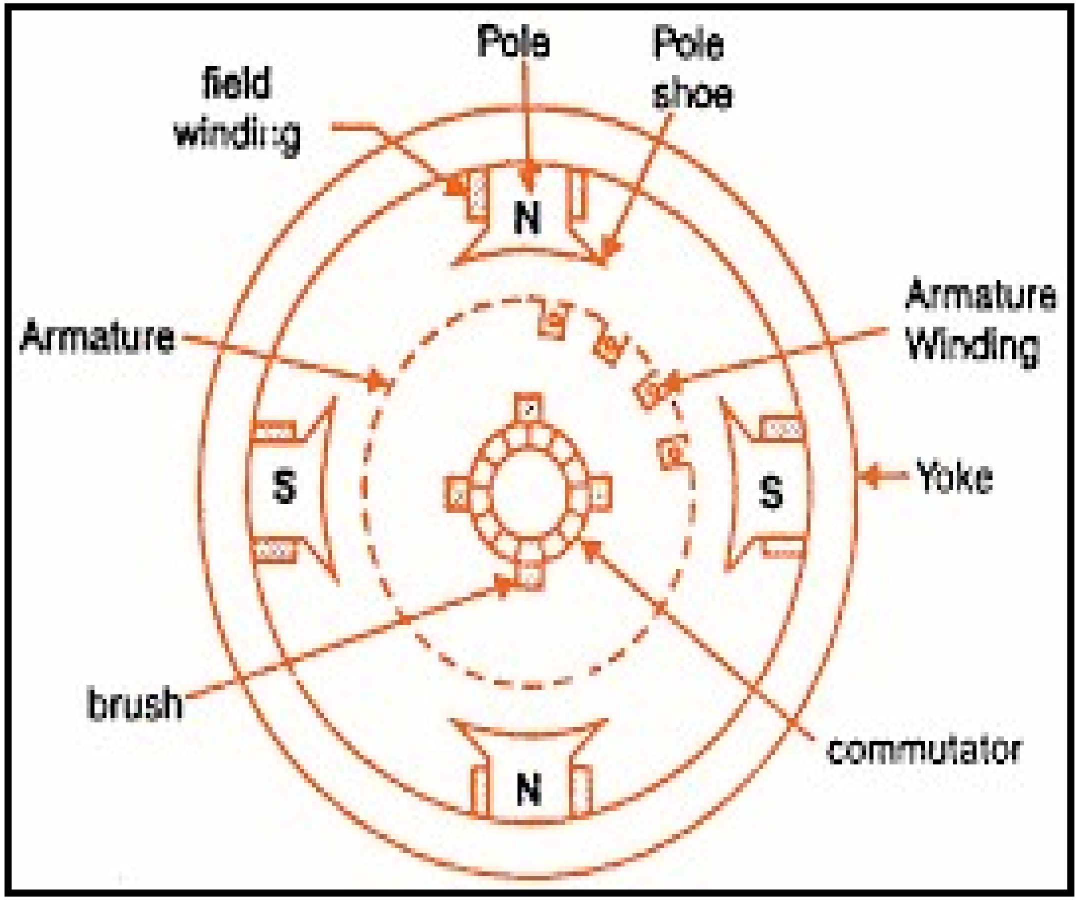
CONSTRUCTION OF DC MOTOR



POLES

- Pole of a dc motor is an electromagnet.
- Field winding is wound over the poles.
- Poles produces magnetic flux when the field winding is excited.

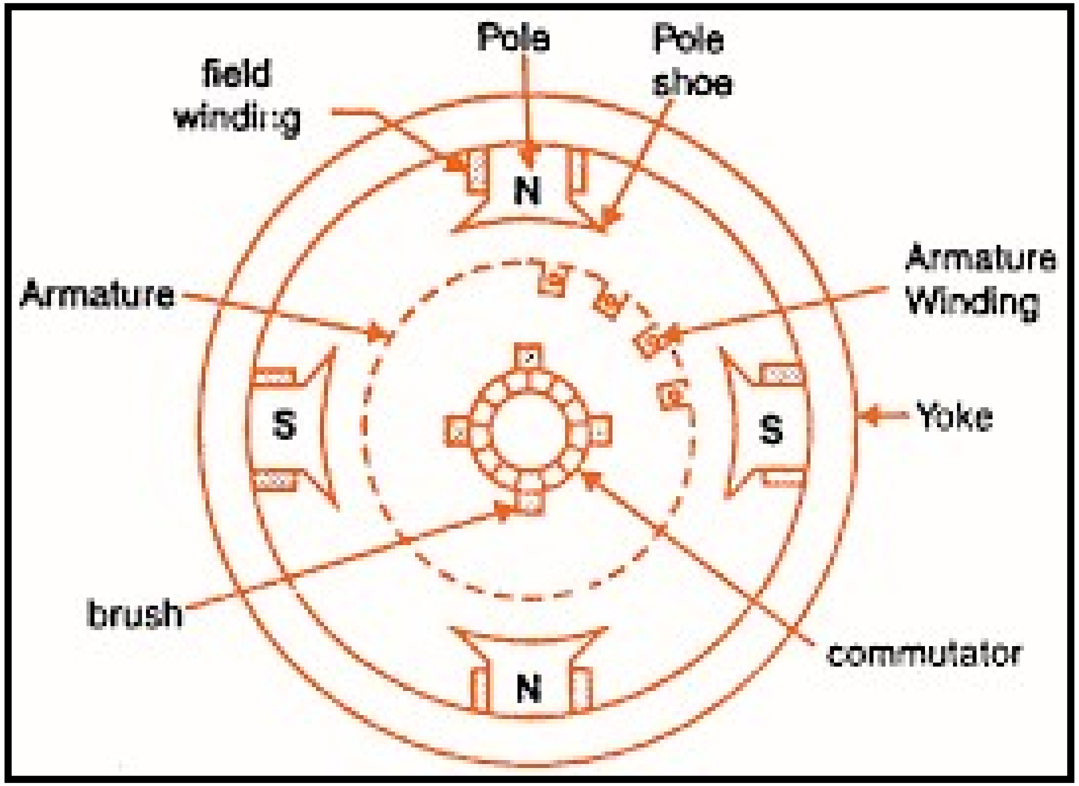
CONSTRUCTION OF DC MOTOR



ARMATURE

- Armature is a cylindrical drum mounted on shaft in which number of slots are provided.
- Armature conductors/windings are placed in these slots.
- Armature conductors are interconnected to form the armature winding.

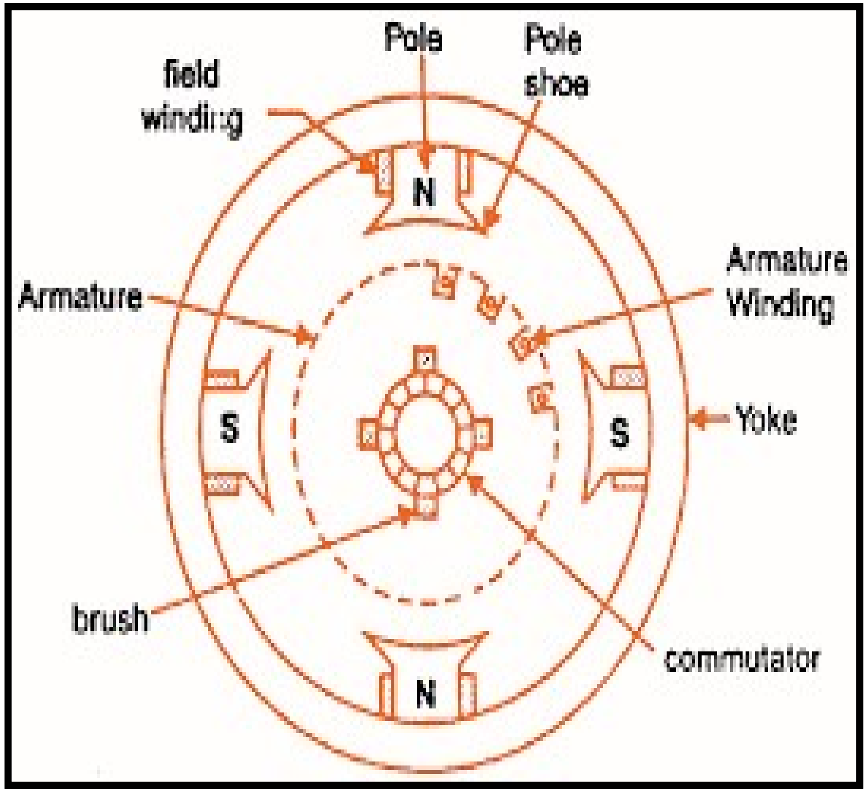
CONSTRUCTION OF DC MOTOR



COMMUTATOR

- Commutator is a cylindrical drum mounted on the shaft along with armature core.
- It collects the current from armature conductors and passed it to the external load via brushes.

CONSTRUCTION OF DC MOTOR



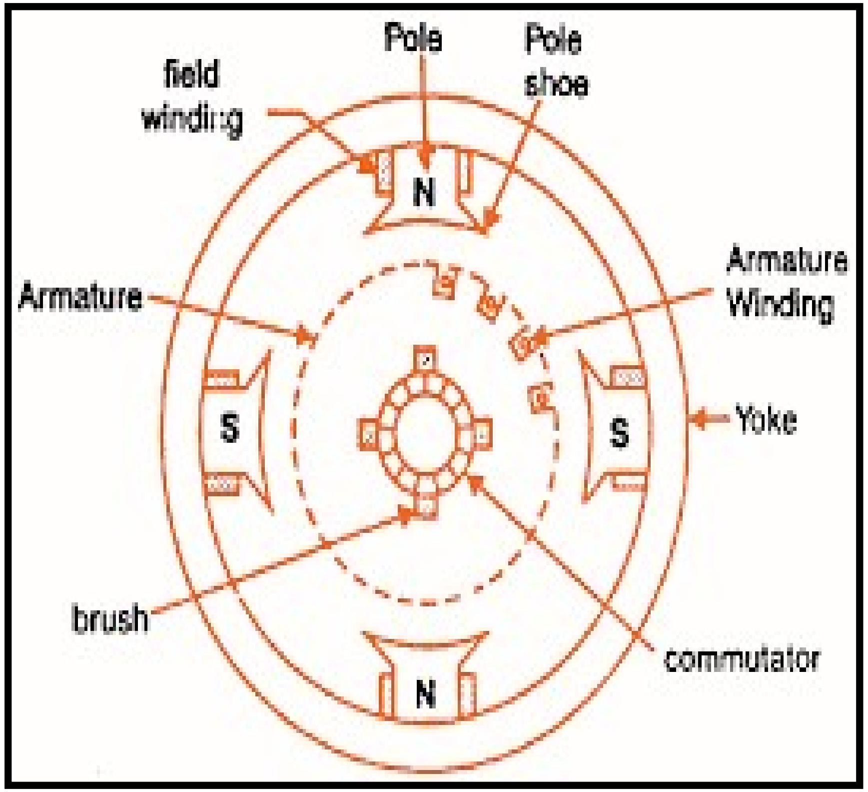
BRUSHES

- Commutator is rotating. So it is not possible to connect the load directly to it.

- Hence current is conducted from the armature to the external load by the carbon brushes which are held against the surface of commutator by springs.

- When armature winding of a dc motor starts rotating in magnetic flux produced by field winding, it cuts the lines of magnetic flux.

CONSTRUCTION OF DC MOTOR



BRUSHES

- According to Faraday's laws of electromagnetic induction, there will be an induced emf in the armature winding.
- As per Lenz's law, this induced emf acts in opposite direction to the armature supply voltage. Emf is called as back emf (E_b).

TYPES OF DC MOTOR

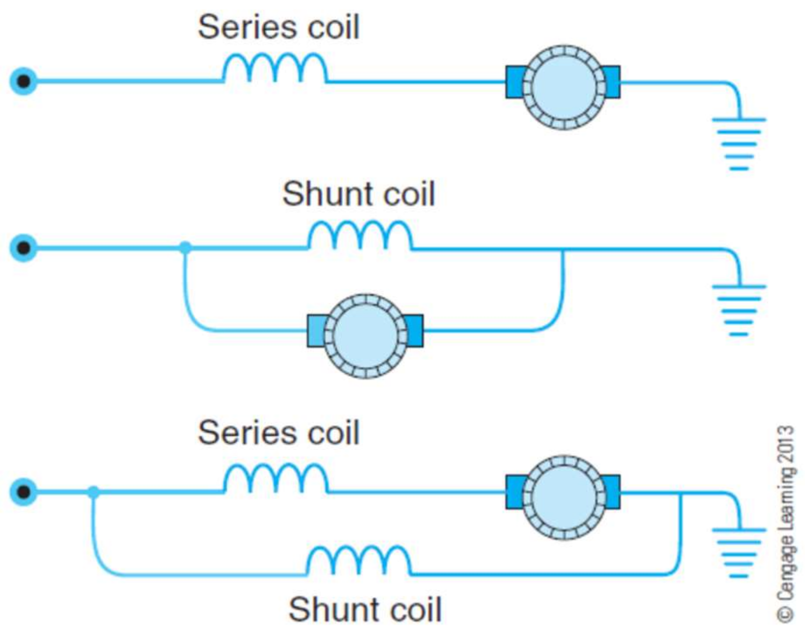


Figure 3-14 The various ways the field windings may be connected to the brushes in DC motors.

ARMATURE MAY BE WIRED

- **Armature windings are in series with field windings - Series motor**
- **Armature windings are in parallel or shunted across the armature -Shunt motors**
- **Combination of series and shunt wiring (compound motors)**

BRUSHLESS DC MOTORS (BLDC)

- BLDC is similar to a Brushed DC Motor.

- BLDC doesn't use brushes for commutation. Rather they are electronically commutated.

- In Brushed DC Motors, the brushes are used to transmit power to rotor as they turn in a fixed magnetic field.

- BLDC motor used electronic commutation and thus eliminates the mechanically torn brushes.

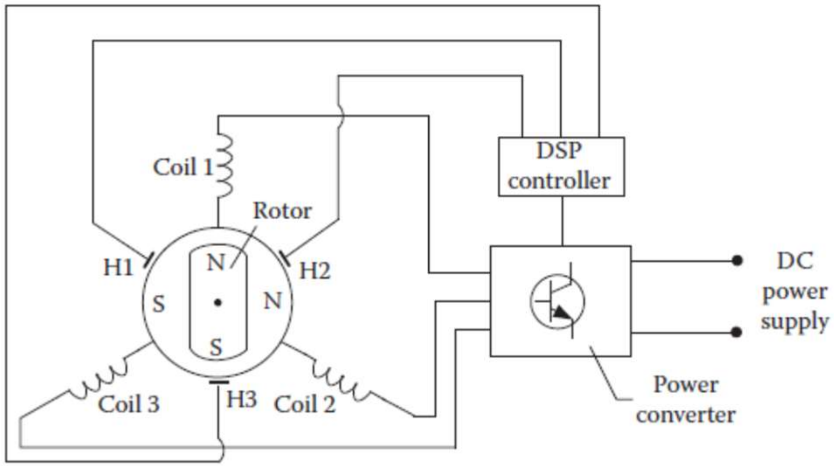


FIGURE 7.42
BLDC motor.

BRUSHLESS DC MOTORS (BLDC)

- BLDC motor drive consists mainly of BLDC machine, digital signal processor
- (DSP)-based controller, and the power-electronics-based power converter, as shown in Figure 7.42.
- Position sensors H1, H2, & H3 sense the position of the machine rotor.
- Rotor position information is fed to the DSP-based controller, which in turn supplies gating signals to the power converter by turning on & off the proper stator pole windings of m/c.
- In this way, the torque and speed of the machines are controlled.

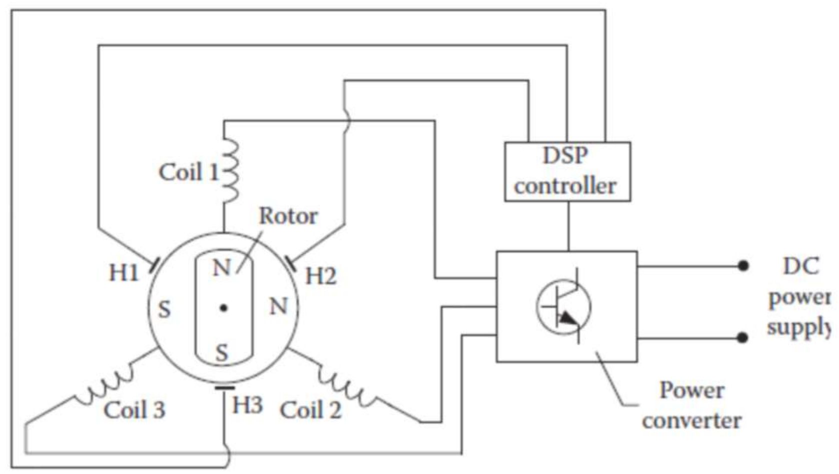


FIGURE 7.42
BLDC motor.

BLDC Motor

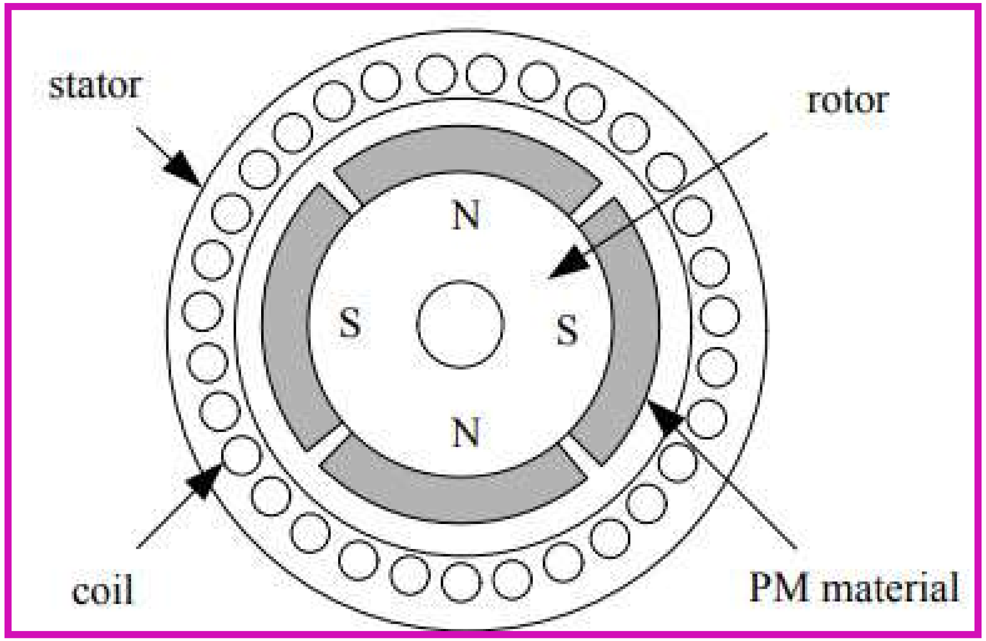
- **Difference between a brushed & brushless motors is the replacement of mechanical commutator with an electric switch circuit.**

- **BLDC Motor is a type of synchronous motor in which magnetic field generated by stator & rotor revolve at same frequency.**

- **BLDC Motors are available in 3 configurations: Single phase, two phase and three phase.**

- **Out of these, the three phase BLDC is the most common one.**

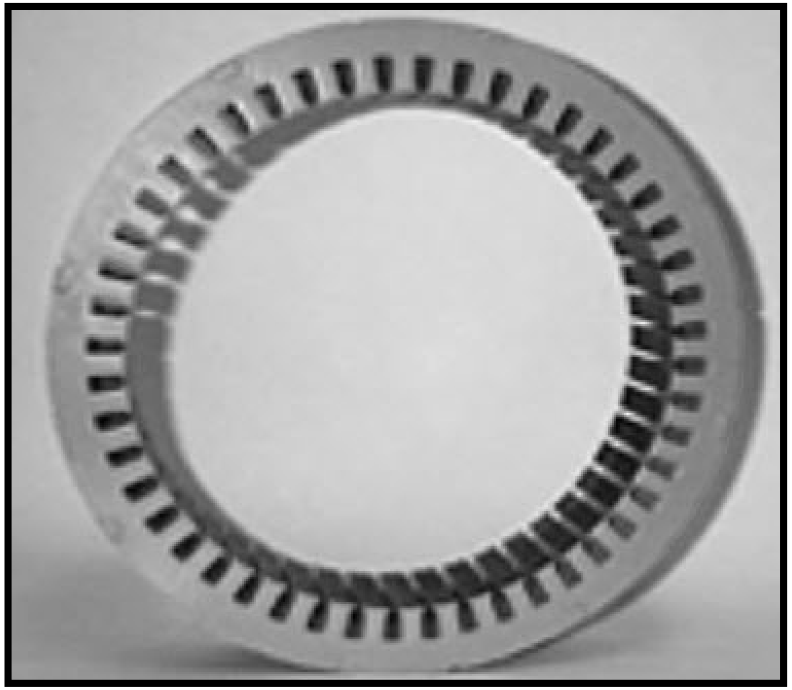
CONSTRUCTION OF BLDC MOTOR



Stator

- Made up of stacked steel laminations with axially cut slots for winding.
- Winding in BLDC are slightly different than that of the traditional induction motor.

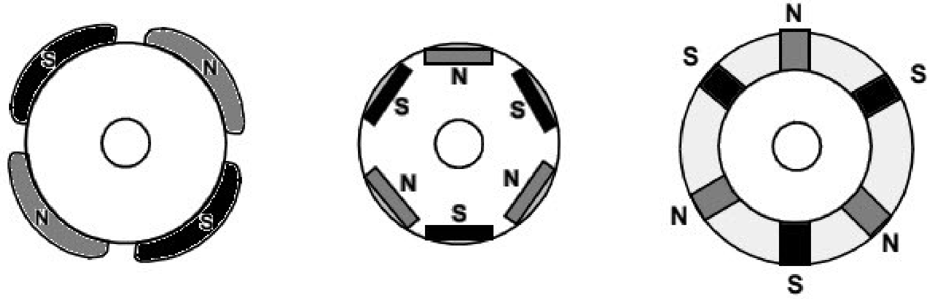
CONSTRUTION OF BLDC MOTOR



STATOR

- BLDC motors consists of three stator windings that are connected in star or ‘Y’ fashion (without a neutral point).
- Based on coil interconnections, stator windings are further divided into Trapezoidal & Sinusoidal Motors.

ROTOR



- Rotor of BLDC Motor is made up of permanent magnets (usually, rare earth alloy magnets like Neodymium (Nd), Samarium Cobalt (SmCo) and alloy of Neodymium, Ferrite and Boron (NdFeB)).
- No of poles can vary between two and eight with North (N) & South (S) poles placed alternately.
- Three different arrangements of poles.
- In case I-magnets are placed on outer periphery of the rotor.
- II configuration is called magnetic-embedded rotor, where rectangular permanent magnets are embedded into the core of the rotor.
- In 3rd case, magnets are inserted into iron core of rotor.

POSITION (HALL)SENSOR

- Since there are no brushes in BLDC Motor, commutation is controlled electronically. In order to rotate motor, windings of the stator must be energized in a sequence & position of rotor (i.e. North & South poles of rotor).

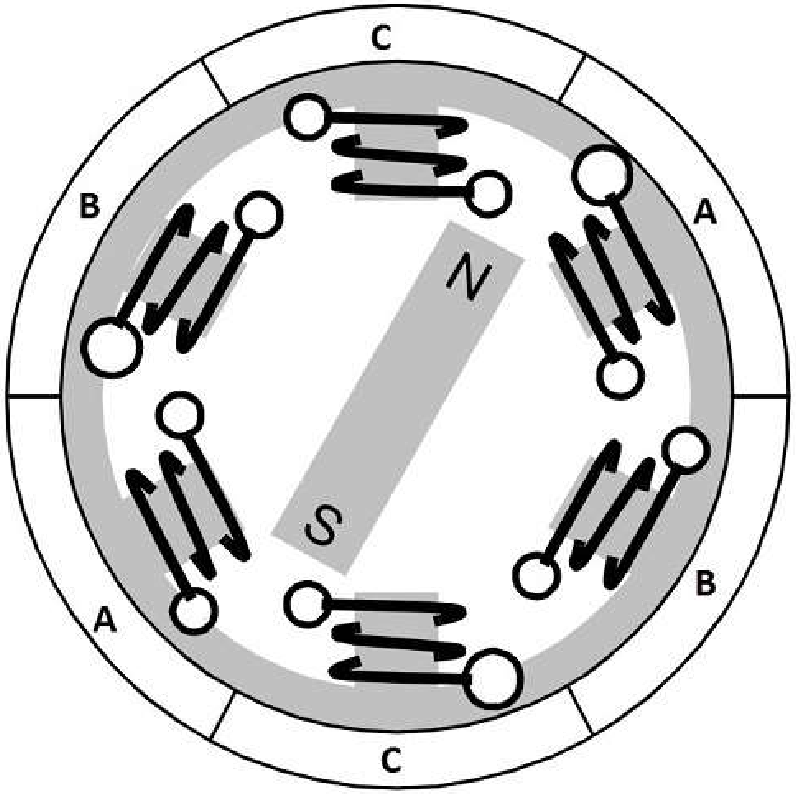
- Position Sensor, works on principle of Hall Effect is generally used to detect the position of rotor and transform it into an electrical signal.

- BLDC Motors use three Hall Sensors that are embedded into the stator to sense the rotor's position.

- Output of Hall Sensor will be either HIGH or LOW depending on whether the North or South pole of the rotor passes near it.

- By combining the results from three sensors, the exact sequence of energizing can be determined.

WORKING



- Stator designated as A, B & C.
- Replace the rotor with a single magnet.
- When a current is applied through a coil, a magnetic field is generated and the orientation of the field lines i.e. the poles of the generated magnet.
- Using this principle, if we supply current to the coil A so that it will generate a magnetic field and attract the rotor magnet. The position of the rotor magnet will shift slightly clockwise and will align with A.
- If we now pass current through coils B and C one after the other (in that order), the rotor magnet will rotate in clock wise direction.

Advantages of BLDC Motors

- **High efficiency: BLDC motors are the most efficient of all electric motors due to the use of PMs for excitation, which consume no power. Absence of mechanical commutators and brushes means low mechanical friction losses & therefore, higher efficiency.**
- **Compactness: Introduction of high-energy-density magnets (rare-earth magnets) has made it possible to achieve very high-flux densities in BLDC motors which makes it possible to achieve high torque, & allows to make the motor small & light.**
- **Ease of control: BLDC motor can be controlled as easily as a DC motor because the control variables are easily accessible and constant throughout the operation of the motor.**

Advantages of BLDC Motors

- **Ease of cooling: There is no current circulation in the rotor. Therefore, the rotor of a BLDC motor does not heat up. Only heat production is on the stator, which is easier to cool than rotor because it is static & on the periphery of the motor.**
- **Low maintenance, great longevity, and reliability: Absence of brushes & mechanical commutators reduces the need for associated regular maintenance and reduces the risk of failure associated with these elements. Longevity is therefore only a function of the winding insulation, bearings, and magnet life length.**
- **Low noise emissions: There is no noise associated with the commutation because it is electronic and not mechanical.**

Disadvantages of BLDC Motors

- **Cost: Rare-earth magnets are much more expensive than other magnets and result in an increased motor cost.**
- **Limited constant power range: Large constant power range is crucial to achieving high vehicle efficiencies. PM BLDC motor is incapable of achieving a maximum speed greater than twice the base speed.**
- **Safety: Large rare-earth PMs are dangerous during the construction of motor because flying metallic objects are attracted to them. There is also a danger in the case of vehicle wreck if the wheel spins freely: the motor is still excited by its magnets, high voltage is present at the motor terminals, which could endanger passengers.**

Disadvantages of BLDC Motors

- **Magnet demagnetization: Magnets can be demagnetized by large opposing magnetomotive forces and high temperatures. The critical demagnetization force is different for each magnet material. Great care must be taken in cooling the motor, especially if it is compact.**

- **High-speed capability: Surface-mounted PM motors cannot reach high speeds because of limited mechanical strength of the assembly between rotor yoke & PMs.**

3-PHASE INDUCTION MOTOR

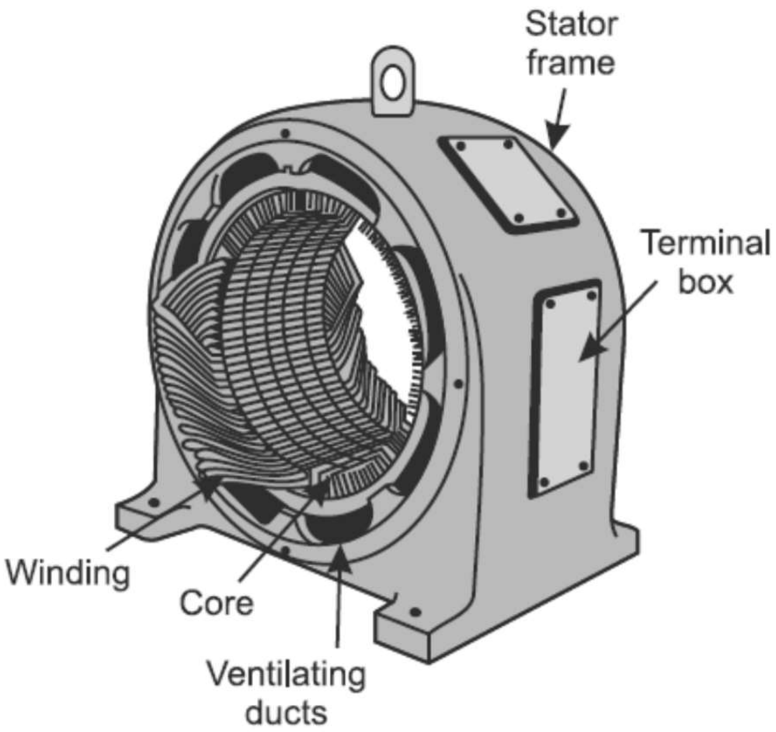


Fig. 9.1 Stator

- **Consists of stator & rotor.**
- **Stator: Stationary part of motor. It has three main parts (*i*) Outer frame, (*ii*) Stator core (*iii*) Stator winding.**
- **Outer frame: Outer body of motor used to support stator core & to protect inner parts.**
- **For small machines, frame is casted but for large machines it is fabricated.**
- **To place the motor on the foundation, feet are provided in the outer frame as shown in Fig.**

3-PHASE INDUCTION MOTOR

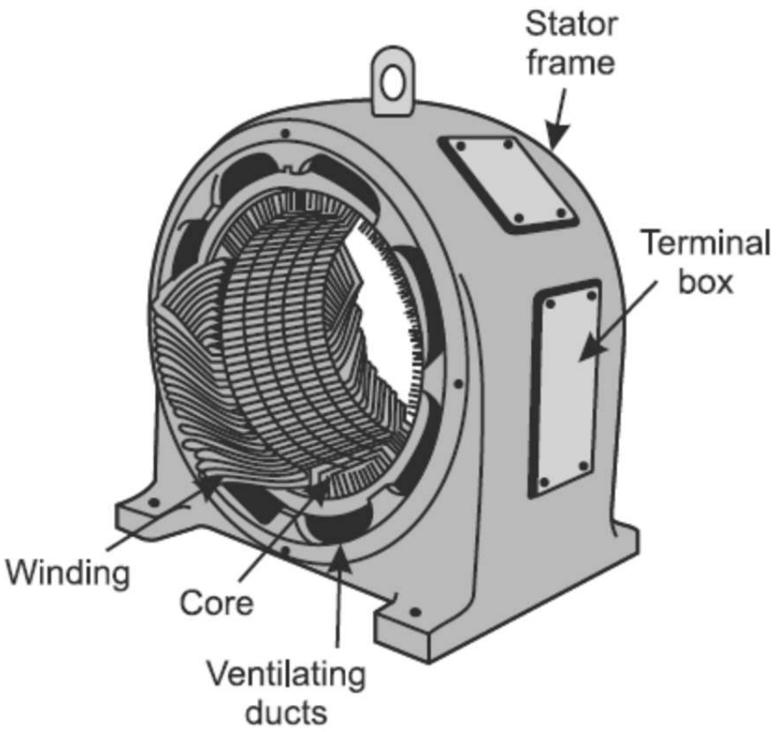


Fig. 9.1 Stator

- **Stator core:** **When AC supply is given, an alternating flux is set -up in stator core which produces hysteresis & eddy current loss.**
- **To minimise these losses, core is made of high grade silicon steel stampings. Stampings are assembled under hydraulic pressure and are keyed to the frame.**
- **Each stamping is insulated from the other with a thin varnish layer.**
- **Thickness to stamping usually varies from 0.3 to 0.5 mm. Slots are punched on the inner periphery of the stampings to accommodate stator winding.**

3-PHASE INDUCTION MOTOR

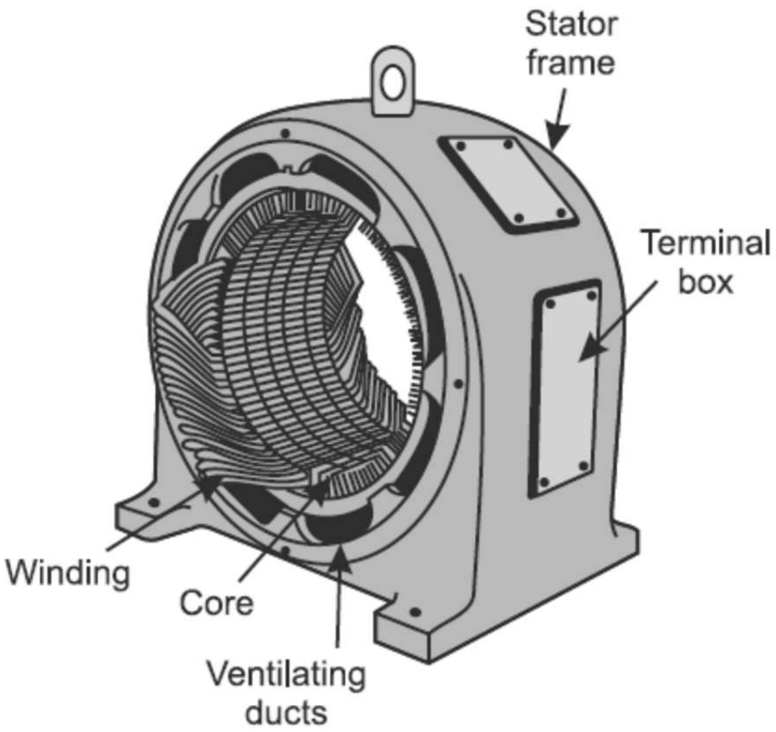


Fig. 9.1 Stator

- **Stator winding**: Stator core carries a three phase winding.
- Six terminals of the winding (two of each phase) are connected in the terminal box of the machine.
- Stator of the motor is wound for definite number of poles, exact number is determined by the requirement of speed.
- Greater the number of poles, the lower is the speed & vice-versa.

3-PHASE INDUCTION MOTOR

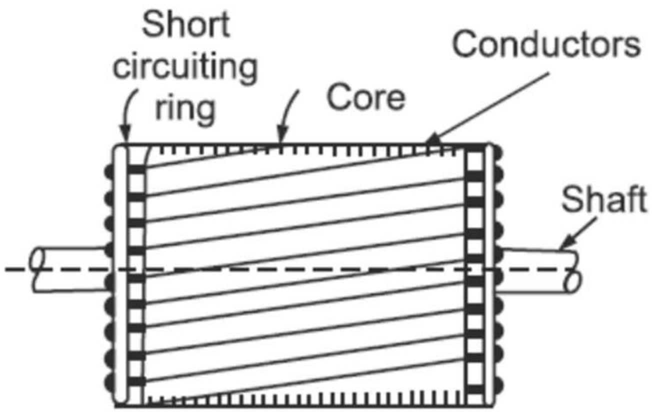


Fig. 9.3 Squirrel cage rotor

- **Rotor: Rotating part of motor is called rotor.**
- **Two types: (i) Squirrel cage rotor (ii) Phase wound rotor.**
- **Squirrel cage rotor: Motors in which these rotors are employed are called Squirrel cage induction motors. Simple & rugged construction.**
- **Squirrel cage rotor consists of a laminated cylindrical core having semi-closed circular slots at the outer periphery. Cu or Al bar conductors are placed in these slots and short circuited at each end by Cu or Al rings, called short circuiting rings.**
- **Rotor winding is permanently short-circuited & no external resistance is added in rotor circuit.**
- **Slots are not parallel to the shaft but these are skewed.**

3-PHASE INDUCTION MOTOR

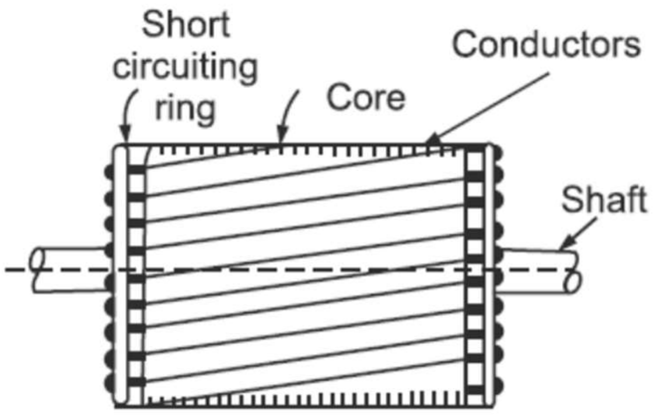


Fig. 9.3 Squirrel cage rotor

- **Skewing provides the following advantages:**
- **Humming is reduced, that ensures quiet running.**
- **At different positions of the rotor, smooth and sufficient torque is obtained.**
- **Reduces the magnetic locking of the stator and rotor**
- **Increases the rotor resistance due to the increased length of the rotor bar conductors.**

3-PHASE INDUCTION MOTOR

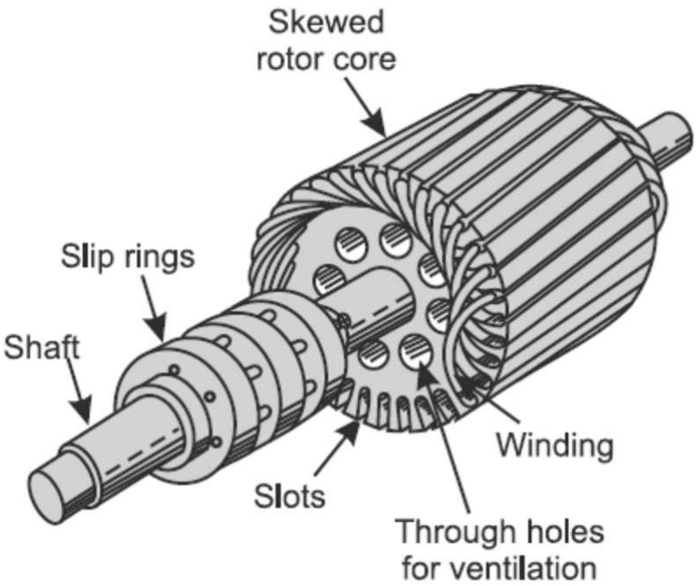


Fig. 9.4 Phase wound rotor

Phase wound rotor***: A*****lso known as slip ring rotor and the motors in which these rotors are employed are known as *phase wound IM*. This rotor is also cylindrical in shape which consists of large number of stampings.**

- **A number of semi-closed slots are punched at its outer periphery. A 3-phase insulated winding is placed in these slots. Rotor is wound for same number of poles as that of stator. Rotor winding is connected in star & remaining three terminals are connected to slip rings.**
- **Rotor core is keyed to shaft. Similarly, slip-rings are also keyed to the shaft but these are insulated from shaft. A mild steel shaft is passed through the centre of rotor and is fixed to it with key. The purpose of shaft is to transfer mechanical power.**

3-PHASE INDUCTION MOTOR

- **When 3-phase supply is given to the stator winding a revolving field is set up in stator core. Resultant magnetic field set-up by the stator core, at any instant. The direction of the resultant field is marked by an arrow head *Fm*. As per the supply sequence, let this field is rotating in an anti-clockwise direction at synchronous speed.**

- **Revolving field is cut by the stationary rotor conductors and an emf is induced in rotor conductors. Since the rotor conductors are short circuited, current flows through them in the direction. A resultant field *Fr* is set-up by the rotor current carrying conductors.**

3-PHASE INDUCTION MOTOR

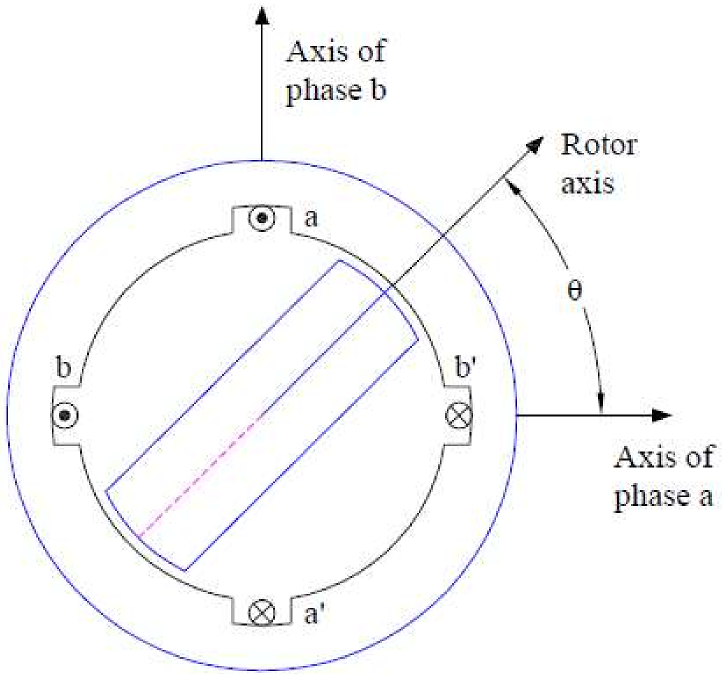
- This field tries to come in line with the stator revolving field *Fm*, due to which an electromagnetic torque *Te* develops and rotor starts rotating in same direction as that of stator revolving field. Rotor picks up speed and tries to attain the synchronous speed but fails to do so. It is because if the rotor attains the synchronous speed then the relative speed between revolving stator field and rotor will be zero, no emf will be induced in rotor conductors. No emf means no current, no rotor field *Fr* and hence no torque is produced. Thus, *an induction motor can never run at synchronous speed*. It always runs at a speed less than synchronous speed. Since, *the principle of operation of this motor depends upon electromagnetic induction, hence the name induction motor.*

https://www.youtube.com/watch?v=AQqyGNOP_3o

SWITCHED RELUCTANCE MOTOR (SRM)

- SRM is similar to BLDC motor. Difference is, it does not use PM .
- Rotor is a form of soft iron and is attracted to the magnetized stator.
- SRM is also known as Variable Reluctance Motor.
- Works on the principle of variable reluctance. This means, the rotor always tries to align along the lowest reluctance path.
- As name suggests, a switching inverter is required for the operation of SRM.

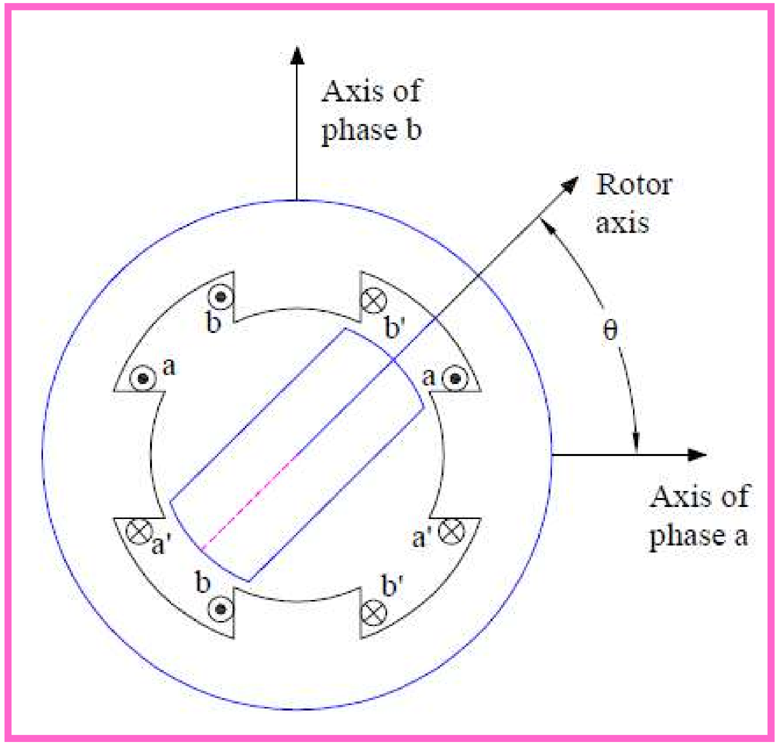
SWITCHED RELUCTANCE MOTOR (SRM)



- SRM comprises of a non-salient stator and a salient two pole rotor.
- Rotor do not have any winding wound over it but the stator have two phase winding as shown.

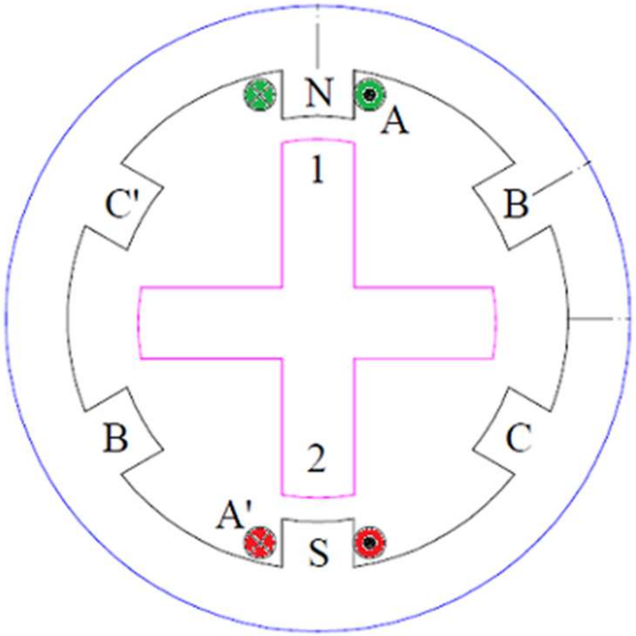
- No. of phase winding on stator may be more than two. Since the rotor is of salient construction, the inductance of stator phase winding varies with rotor position. The inductance is minimum when rotor axis & stator phase winding axis coincides whereas it is maximum when both axis are in quadrature.

SRM

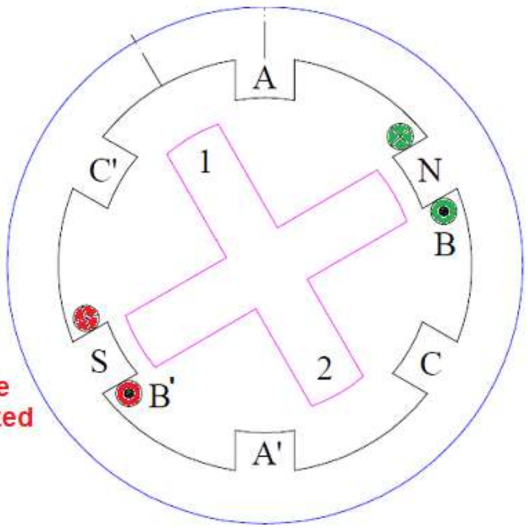


Doubly Salient Construction:

- **Unlike singly salient type, stator of doubly salient SRM is of salient construction and consists of four poles as shown. The rotor do not carry any winding and is of salient construction but have two poles.**
- **This type of SRM is a heteropolar motor where the <u>numbers of stator and rotor poles</u> are not same.**
- **Stator phase windings are concentrated winding. These concentrated windings on radially opposite poles are either connected in series or parallel to result into two phase winding on stator.**
- **A doubly salient type SRM produces more torque as compared to singly salient type for the same size. Therefore a doubly SRM is more common and widely used.**



A Phase Energized



B Phase Energized

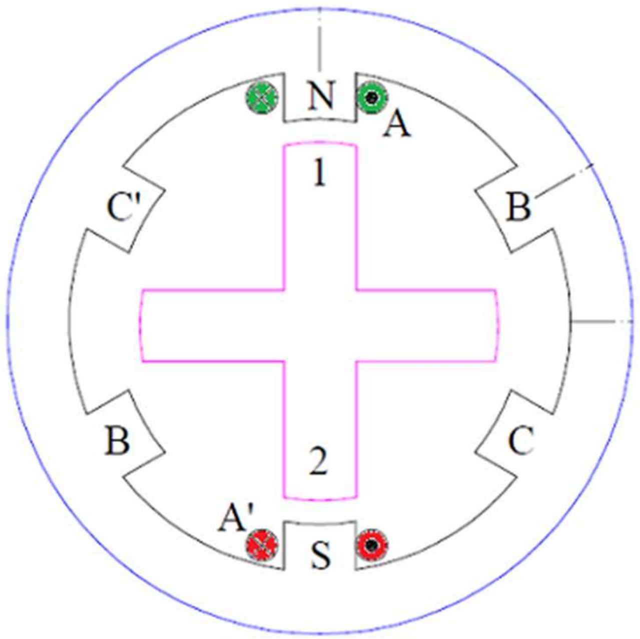
Working:

- **Magnetic flux have a tendency to flow through lowest reluctance path, therefore rotor always tends to align along the minimum reluctance path. This is the basic working principle of SRM.**

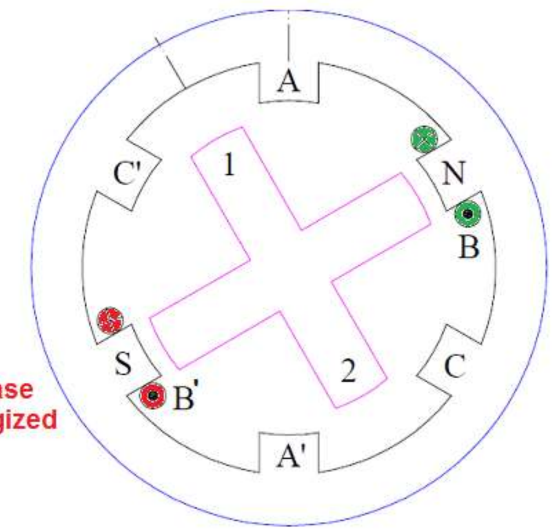
- **Therefore, when stator phase winding A is energized, rotor align along this phase as shown.**

- **When stator phase winding A is de-energized and winding B is energized, rotor align itself along B phase as shown.**

- **Similarly, rotor occupies a position along phase winding C when this phase is energized.**



A Phase Energized



B Phase Energized

Working:

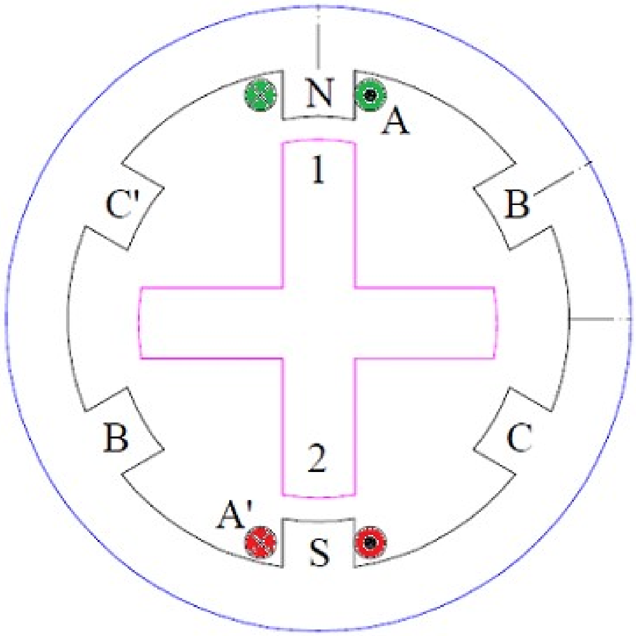
- **Magnetic flux have a tendency to flow through lowest reluctance path, therefore rotor always tends to align along the minimum reluctance path. This is the basic working principle of Switched Reluctance Motor or Variable Reluctance Motor.**

- **Therefore, when stator phase winding A is energized, the rotor align along this phase as shown in figure below.**

- **When stator phase winding A is de-energized and winding B is energized, the rotor align itself along B phase as shown.**

- **Similarly, the rotor occupies a position along phase winding C when this phase is energized.**

Working:



- Thus rotor rotation in clockwise direction is achieved by energizing phase winding in a ABC sequence. If rotor rotation in anti-clockwise direction is require, stator phase winding must be energized in ACB sequence.

- It must also be noted that, a particular phase winding must be energized / de-energized in synchronism with rotor position. This means as soon as rotor align along the A phase, B phase must be energized and A phase must be de-energized if clockwise rotor rotation is required.

SWITCHED RELUCTANCE MOTOR (SRM)

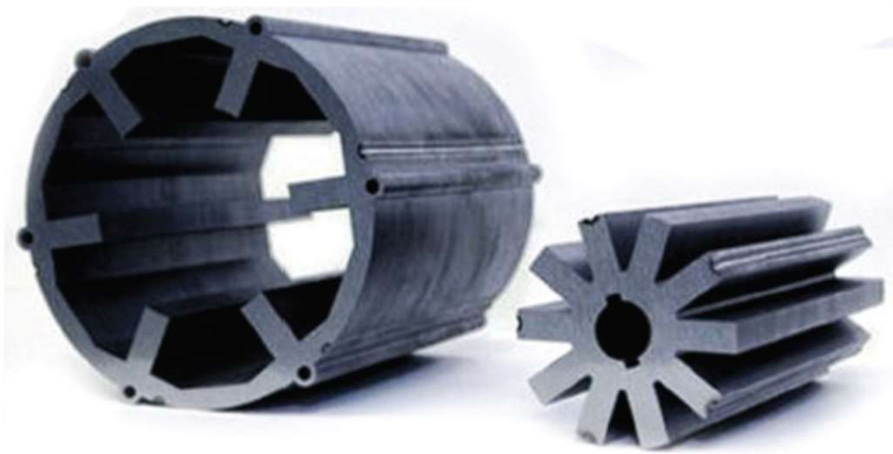


Figure 6.12 Switched reluctance motor stator (left) and rotor without windings on the stator (Source: HEVT)

- Key advantage: No expensive rare earth magnets are needed.
- Raw materials for these are a source of political discussion, with China being the main supplier.
- Overall the M/C is very simple & cheap.
- Early SRMs were noisy but this has been solved by more accurate switching control.
- A company (HEVT) has developed a potentially game-changing alternative to induction and permanent magnet motors.

INVERTOR/CONVERTOR

- **An AC power inverter converts battery's DC voltage into three-phase AC voltage to power traction motor.**
- **Increase in current in three-phase windings creates more torque, & speed is increased by increasing frequency of the voltage. Output voltage varies according to the demands of driver and vehicle. Normally power inverter is controlled by an electronic control module.**
- **Output from a inverter is calculated using input signals from accelerator pedal, motor's shaft speed sensor, motor's direction sensor, brake pedal. Inverter is essential to the operation of motor and, if it fails, motor cannot run.**

INVERTOR/CONVERTOR

- **EVs that use DC motors do not need an inverter. Inverter is liquid-cooled, and the heat from inverter can be used to supplement passenger compartment's heater to save energy. This is done automatically whenever the controls are set for heat.**

- **In DC systems, voltage and current from battery pack merely need to be controlled. Actual current flow to the motor is regulated by the controller.**

INVERTOR/CONVERTOR

- **Remember, a DC motor draws a maximum current and produces its maximum torque when it has zero speed. If a DC converter fails, it is possible for a motor to receive maximum current, and the vehicle can suddenly move with the highest possible torque from the motor. This could be very dangerous and is one of the primary reasons major manufacturers use AC systems in their vehicles.**

- **DC/DC converter reduces the voltage from the main battery pack to provide power for the 12-V accessories, such as head and taillights, wipers, radio, windows, power steering pump & so on.**

INVERTOR/CONVERTOR

DC/DC converter also keeps the 12-V auxiliary battery charged. The auxiliary battery may be used as an emergency power source if the main converter fails. Instantaneous power demands can be provided by an ultra-capacitor wired in parallel to the converter's output. The ultra-capacitor takes care of power demands for a fraction of a second.

SERIES HYBRID ELECTRIC DRIVE TRAIN (ELECTRICAL COUPLING)

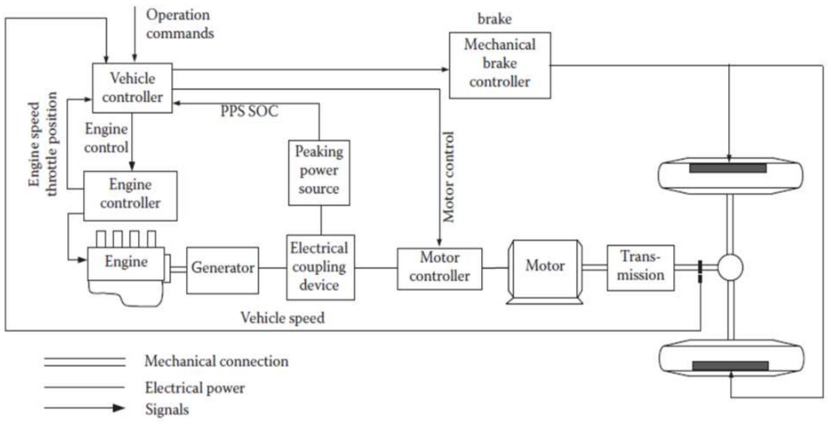


FIGURE 8.1
Configuration of a typical series hybrid electric drivetrain.

- Objective of developing a series HEV was aimed at extending drive range by adding an engine/alternator system to charge batteries.
- Typical series HEDT configuration is shown in Figure.
- Vehicle is propelled by a traction motor. Traction motor is powered by a battery pack and/or an engine/generator unit.
- Powers of both power sources are merged together in a power electronics-based & controllable electrical coupling device.
- Many operation modes are available to choose from, according to the power demands of the driver & operational status of drivetrain system.

SERIES HYBRID ELECTRIC DRIVE TRAIN (ELECTRICAL COUPLING)

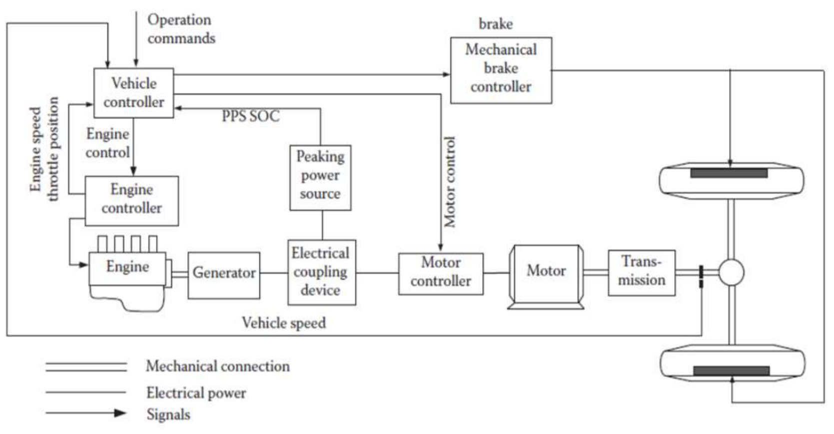


FIGURE 8.1
Configuration of a typical series hybrid electric drivetrain.

- Vehicle performance (in terms of acceleration, gradeability, and maximum speed) is completely determined by the size & characteristics of traction motor drive.
- In series HEDT, engine/generator system is mechanically decoupled from drive wheels.
- Speed and torque of the engine are independent of vehicle speed and traction torque demand, and they can be controlled at any operating point.
- Due to the mechanical decoupling of the engine from drive wheels, this optimal engine operation is realizable.

SERIES HYBRID ELECTRIC DRIVE TRAIN (ELECTRICAL COUPLING)

OPERATING MODES:

- **Hybrid Traction mode**
- **Peak power source traction mode**
- **Engine/Generator traction mode**
- **PPS charge from engine /generator**
- **Regenerative braking mode**

SERIES HYBRID ELECTRIC DRIVE TRAIN (ELECTRICAL COUPLING)

Hybrid Traction mode:

- When a large amount of power is demanded, both the engine/generator and peaking power source (PPS) supply their power to the electric motor drive.
- Engine should be controlled to operate in its optimal region for efficiency and emission.
- PPS supplies additional power to meet the traction power demand.

SERIES HYBRID ELECTRIC DRIVE TRAIN (ELECTRICAL COUPLING)

- **Peak power source-alone traction mode:**

PPS alone supplies its power to meet the power demand

- **Engine/generator-alone traction mode:**

Engine/generator alone supplies its power to meet the power demand

SERIES HYBRID ELECTRIC DRIVE TRAIN (ELECTRICAL COUPLING)

PPS charge from engine/generator:

- **When the energy in the PPS decreases to some bottom threshold, PPS must be charged.**
- **This can be done by regenerative braking or by engine/generator.**
- **Engine/generator charging is needed, since regenerative braking charging is insufficient.**
- **Engine/generator power is divided into two parts: one to propel the vehicle &bother to charge the PPS.**

SERIES HYBRID ELECTRIC DRIVE TRAIN (ELECTRICAL COUPLING)

Regenerative braking mode:

When a vehicle brakes, traction motor can be used as a generator, converting part of the kinetic energy of the vehicle mass into electric energy to charge the PPS.

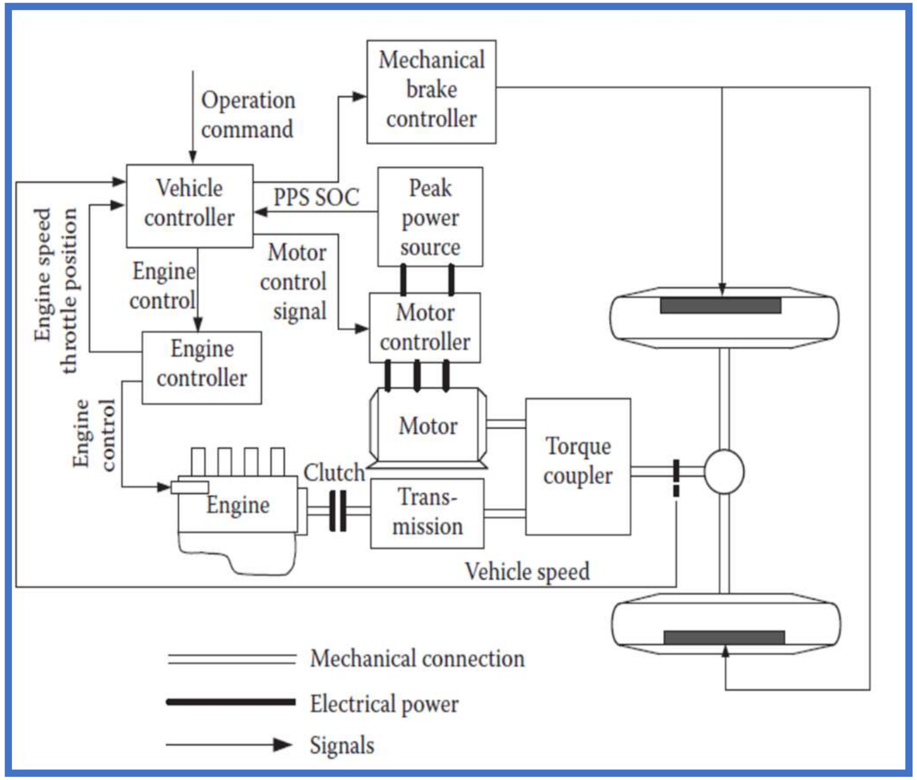
PARALLEL HYBRID ELECTRIC DRIVE TRAIN (MECHANICAL COUPLING)

- Unlike series hybrid drivetrain, parallel or mechanically coupled hybrid drivetrain has features that allow both the engine and the traction motor to apply their mechanical power in parallel directly to the drive wheels.
- Mechanical coupling has two forms: torque and speed couplings. When using conventional IC engines as primary power source, torque coupling is more appropriate as IC engine is a torque source.
- Major advantages of a torque-coupling parallel configuration over a series configuration are: Non necessity of a generator, a smaller traction motor, only part of engine power going through multipower conversion.
- Overall efficiency is higher than in series hybrid.

PARALLEL HYBRID ELECTRIC DRIVE TRAIN (MECHANICAL COUPLING)

- However, control of the parallel hybrid drivetrain may be more complex than that of series hybrid drivetrain because of simultaneous mechanical coupling between engine and drive wheels. There are many possible configurations in a parallel hybrid drivetrain.
- Design methodology for one configuration may not be applicable to others. Each particular configuration may be only applicable to specified operation environment.
- Engine supplies its power to meet base load and electric motor supplies power to meet peak load requirement.

PARALLEL HYBRID ELECTRIC DRIVE TRAIN (MECHANICAL COUPLING)



- Structure of a parallel (torque coupling) hybrid vehicle is shown in Figure.
- Control system of drivetrain consists of a vehicle controller, an engine controller to control engine power, an electric motor controller, mechanical brake controller and a clutch controller.
- Vehicle controller is the highest-level controller. It receives operation command from driver through the accelerator and brake pedals, and other operating variables of the vehicle and its components, which includes vehicle speed, engine speed and throttle position, SOC of the PPS, and so on.

PARALLEL HYBRID ELECTRIC DRIVE TRAIN (MECHANICAL COUPLING)

- **By processing all signals received, based on the embedded drivetrain control algorithm, vehicle controller generates control commands and sends commands to corresponding component controllers.**

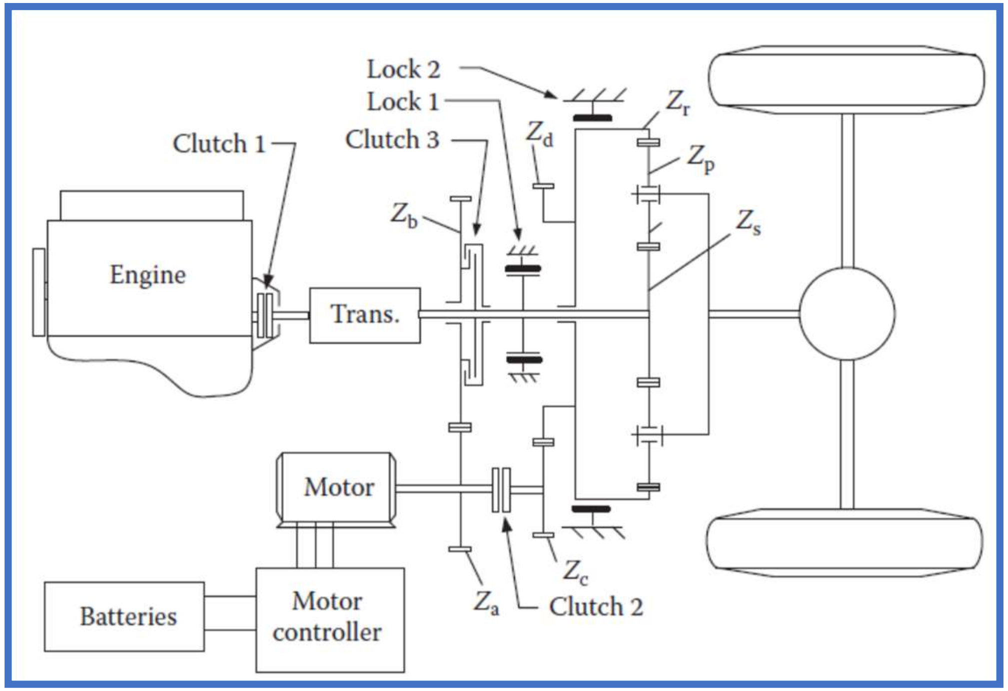
- **Component controllers control the corresponding components to carry out the commands coming from vehicle controller.**

- **Since torque coupler is uncontrollable, the power flow in drivetrain can only be regulated by controlling the power sources, that is, the engine, traction motor, clutch, and mechanical brake.**

Series–Parallel (Torque and Speed Coupling) Hybrid Drive train

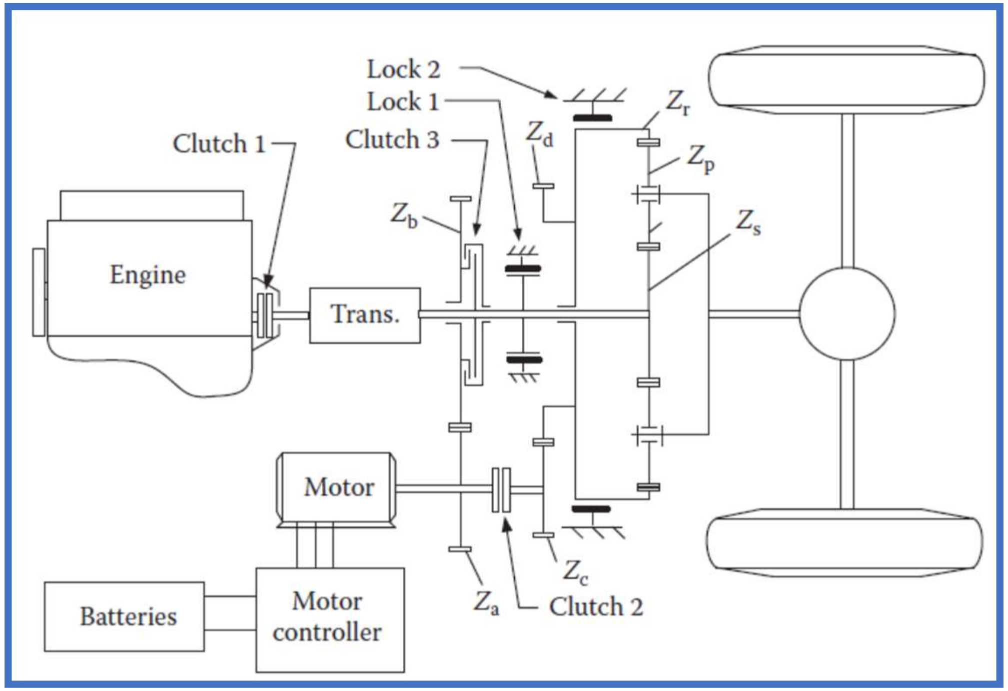
- Series–parallel hybrid drivetrain has some advantages over series (electrical coupling) and parallel (torque or speed coupling) drivetrains.
- Torque and speed coupling in this drivetrain free the engine from drive wheels in the torque and speed constraints. Consequently, instantaneous engine torque and speed can be independent of the load torque and speed of the vehicle.
- Engine can be operated in its high-efficiency region in a similar way as that of the series (electrical coupling) drivetrain. Part of the engine power is directly delivered to drive wheels without experiencing multiform conversion.

Series–Parallel (Torque and Speed Coupling) Hybrid Drivetrain



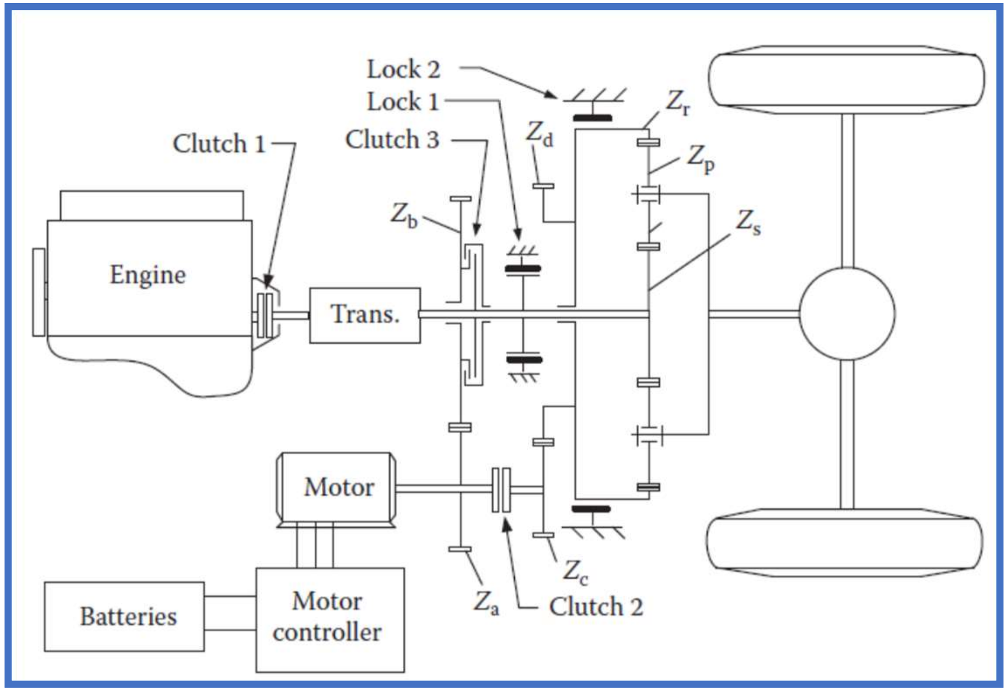
- Series–parallel hybrid drive train can be composed of speed coupling devices such as planetary gears and trans motors. All these configurations have similar features, designs, and control principles.
- By combining torque & speed coupling, one may establish a hybrid drivetrain in which torque-speed-coupling states can be alternately chosen.
- When torque-coupling operation mode is chosen, lock 2 locks the ring gear of the planetary unit to the vehicle frame while clutches 1 and 3 are engaged, and clutch 2 is disengaged.
- Power of engine & motor are added together by adding their torques together through gear Za, Zb & clutch 3 to sun gear shaft.

Series–Parallel (Torque and Speed Coupling) Hybrid Drivetrain



- In this case, planetary gear unit functions only as a speed reducer.
- When speed-coupling mode is chosen as current operating mode, clutches 1 & 2 are engaged, whereas clutch 3 is disengaged, and locks 1 & 2 release the sun gear & ring gear.
- Speed of the yoke, connected to the drive wheels, is a combination of engine speed and motor speed
- With the option to choose the power-coupling mode (torque or speed coupling), power plant has more opportunities to choose its operation manner and operation region to optimize its performance.
- For instance, at low vehicle speeds, torque combination operation mode may be suitable for high acceleration or hill climbing.
- On the other hand, at high vehicle speeds, speed combination mode would be used to keep engine speed in its optimal region.

Series–Parallel (Torque and Speed Coupling) Hybrid Drivetrain



- When clutch 1 is engaged to couple output shaft of transmission to inner rotor shaft of the transmotor, clutch 2 is disengaged to release engine shaft from the inner rotor of the transmotor, and the lock is activated to fix the outer rotor of the transmotor to the vehicle frame.

- Drivetrain then works in torque-coupling mode. On the other hand, when clutch 1 is disengaged, clutch 2 is engaged, and the lock is released, the drivetrain works in speed-coupling mode.

ELECTRONICS IN ELECTRIC VEHICLE

AUTONOMOUS EV CARS

- An autonomous car, also known as a driverless car, self-driving car and robotic car
- Capable of sensing its environment and navigating without human input.
- Sense their surroundings with such techniques as RADAR, LIDAR, GPS & computer vision.
- Capable of updating their maps based on sensory input, allowing the vehicles to keep track of their position even when conditions change or when they enter unknown environments.

GOOGLE SELF DRIVING CAR

- Google Self-Driving Car (SDC), is a project by Google X that involves developing technology for autonomous cars, mainly electric cars.

- May 2014, Google presented a new concept for their driverless car that had neither a steering wheel nor pedals.

- Google made these cars available to the public in 2020.

GOOGLE SELF DRIVING CAR

- Google's autonomous cars include about $150,000 in equipment, including a $70,000 LIDAR system.
- Range finder mounted on the top that uses a 64-beam laser. This laser allows the vehicle to generate a detailed 3D map of its environment.
- Car then takes these generated maps and combines them with high-resolution maps of the world, producing different types of data models that allow it to drive itself.

GOOGLE SELF DRIVING CAR

- Heavy rain or snow produce safety concerns for all autonomous vehicle.

- Other issues are that the cars rely primarily on pre-programmed route data and as a result do not obey temporary traffic lights and, in some situations, revert to a slower ‘extra cautious’ mode in complex unmapped intersections.

GOOGLE SELF DRIVING CAR

- Vehicle has difficulty identifying when objects, such as trash and light debris, are harmless, causing the vehicle to veer unnecessarily.

- LIDAR technology cannot spot some potholes or discern when humans, such as a police officer, are signalling the car to stop.

HACKING

- Hacking: Gaining unauthorized access to data in a system or computer.
- As vehicles are connected to outside world by radio waves, then more opportunities are presented to hackers. Of course manufacturers are working very hard to reduce the likelihood of cars being hacked and are helped in this process by what can be described as ethical hackers.
- Fiat Chrysler recalled 1.4 million vehicles in the USA because hackers had proved they could take control of an SUV over the Internet and steer it into a ditch.
- Certain vehicle models manufactured from 2013 onwards required a software update to stop them from being controlled remotely.

HACKING

- Jonathan Petit, Principal Scientist at the software security company Security Innovation, said he was able to take echoes of a fake car and put them at any location, and do the same with a pedestrian or a wall.

- Using such a system, with a cost of about £40, that uses a kind of Laser pointer, attackers could trick a self-driving car into thinking something is directly ahead of it, causing it to slow down. Or by using numerous false signals, the car would not move at all.

SAFETY GUIDANCE OF E-VEHICLE

BEFORE MAINTENANCE

- Turn OFF the ignition switch and remove the key.
- Switch OFF the battery module switch or de-energize the system.
- Wait for 5 minutes before performing any maintenance procedures on the system which allows any storage capacitors to be discharged.

SAFETY GUIDANCE

DURING MAINTENANCE

- Always wear insulating gloves.
- Always use insulated tools when performing service procedures to the high voltage system.
- This precaution will prevent accidental short-circuits.

SAFETY GUIDANCE

AFTER MAINTENANCE

- Before switching on or re-energizing the battery module after repairs have been completed, make sure that all terminals have been tightened to the specified torque.

- No high-voltage wires or terminals have been damaged or shorted to the body.

- Insulation resistance between each high-voltage terminal of the part you disassembled and the vehicle’s body has been checked.

SAFETY GUIDANCE

PEDESTRIAN SAFETY

- Quietness of EVs is a benefit but can pose a threat to sight and hearing-impaired people, particularly at low speeds.
- Having seen a vehicle, pedestrians are capable of reacting to avoid an accident at vehicle speeds upto 15 mph.
- Research found that tyre noise will alert pedestrians to a vehicle’s presence at speeds greater than 12.4 mph.

HIGH VOLTAGE SAFETY PRECAUTION

- **Follow all safety procedures and do not touch any electric circuit greater than 12 V or 24 V**
- **IEC – International Electrotechnical Commission**

Table 2.2 IEC voltages

IEC voltage range	AC	DC	Defining risk
High voltage (supply system)	>1000 Vrms*	>1500 V	Electrical arcing
Low voltage (supply system)	50–1000 Vrms	120–1500 V	Electrical shock
Extra-low voltage (supply system)	<50 Vrms	<120 V	Low risk

*The root mean square (rms) is a value characteristic of a continuously varying quantity, such as an AC electric current. This is the effective value in the sense of the value of the direct current that would produce the same power dissipation in a resistive load.

Safety First

For EVs, DC voltages between 60 V and 1500 V are referred to as 'high voltage'.

HIGH VOLTAGE SAFETY PRECAUTION

PERSONAL PROTECTIVE EQUIPMENT

Following are recommended for work on high-voltage systems

- Overalls with non-conductive fasteners
- Electrical protection gloves
- Protective footwear; rubberized soles; non-metallic protective toe caps
- Goggles (when necessary).

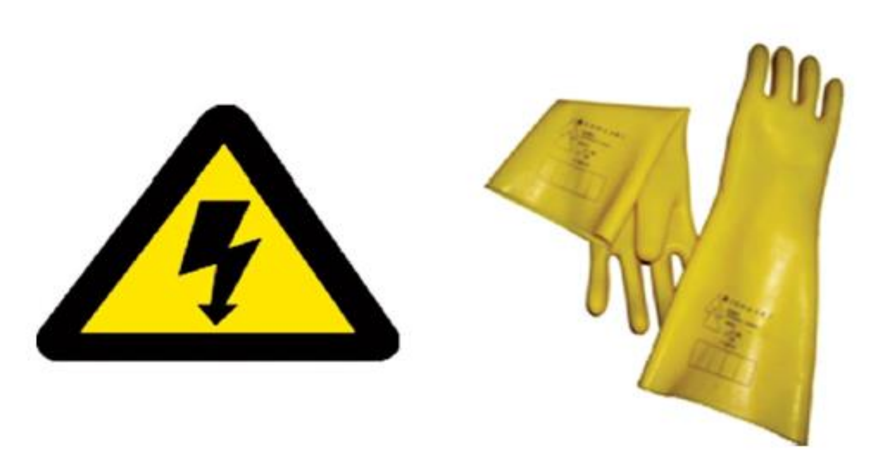


Figure 2.8 Insulated gloves

HIGH VOLTAGE SAFETY PRECAUTION

HIGH-ENERGY CABLES AND COMPONENTS

- EV use high-voltage batteries so that energy can be delivered to a drive motor or returned to a battery pack efficiently in a very short time.
- It is important to be able to correctly identify high-energy cabling and associated components by Colouring/warning symbols/warning signs.

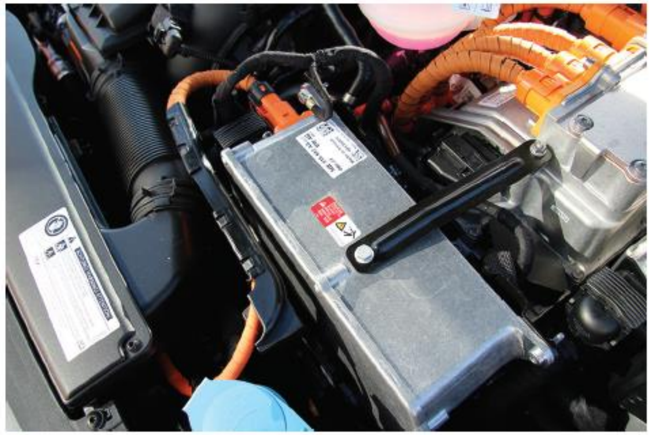
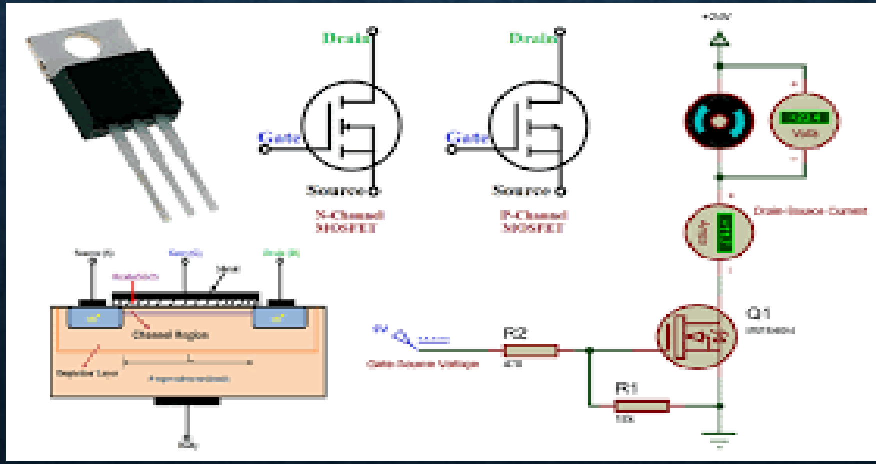


Figure 2.9 Orange high-voltage cables

Figure 2.10 Danger sticker

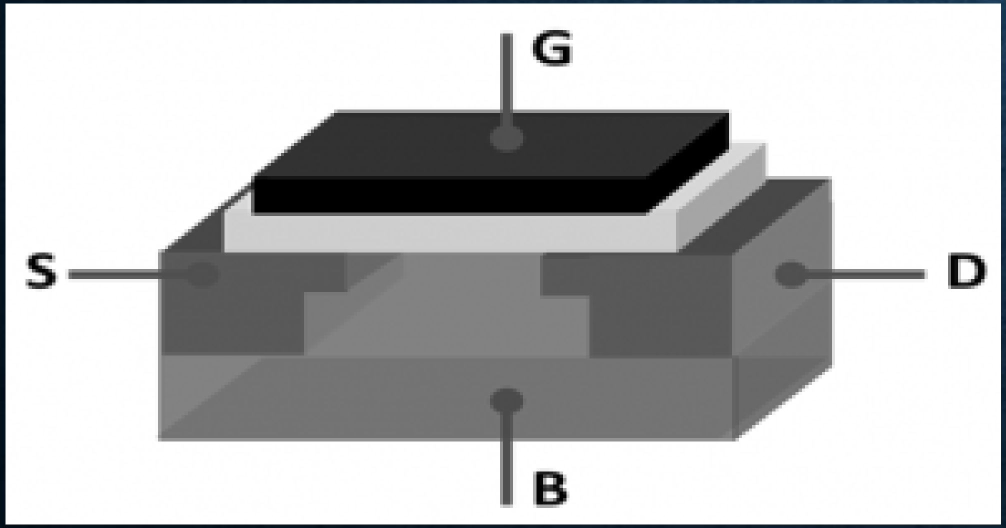
MOSFET

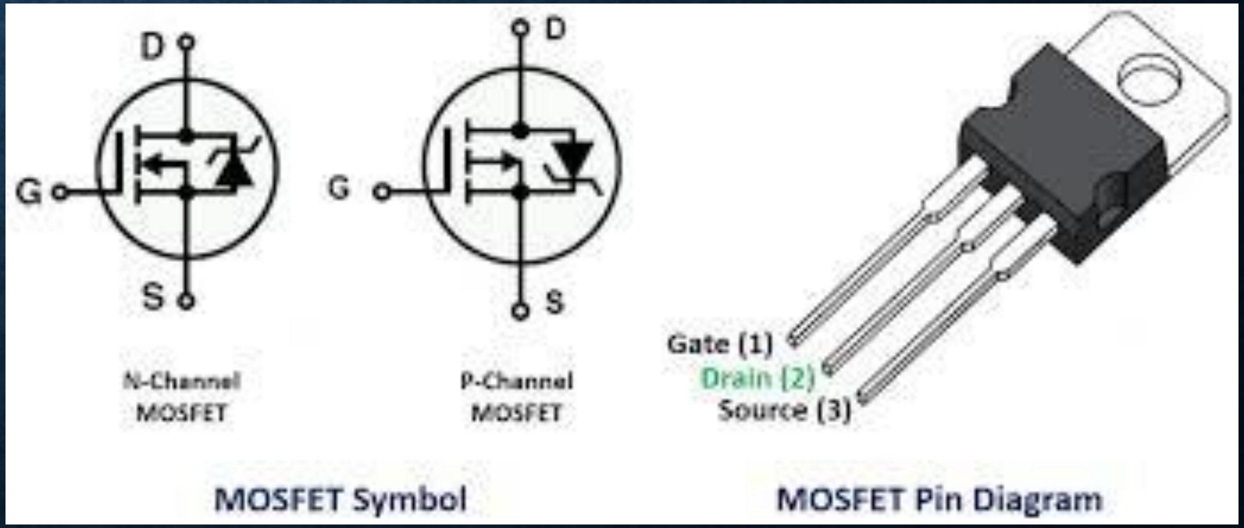
- MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is a semiconductor device used for switching purposes and for the amplification of electronic signals in electronic devices.
- A MOSFET is either a core or integrated circuit where it is designed and fabricated in a single chip because the device is available in very small sizes.
- https://www.youtube.com/watch?v=hleOUSrTCmY



MOSFET

- MOSFET is a four-terminal device having source(S), gate (G), drain (D) and body (B) terminals.
- Body of the MOSFET is in connection with the source terminal thus forming a three-terminal device such as a field-effect transistor.
- MOSFET is considered as a transistor & employed in both analog/digital circuits.





MOSFET

- MOSFET can function in two ways
- Depletion Mode
- Enhancement Mode

Depletion Mode:

When there is no voltage across the gate terminal, the channel shows its maximum conductance. Whereas when the voltage across the gate terminal is either positive or negative, then the channel conductivity decreases.

Enhancement Mode:

When there is no voltage across the gate terminal, then the device does not conduct. When there is the maximum voltage across the gate terminal, then the device shows enhanced conductivity.

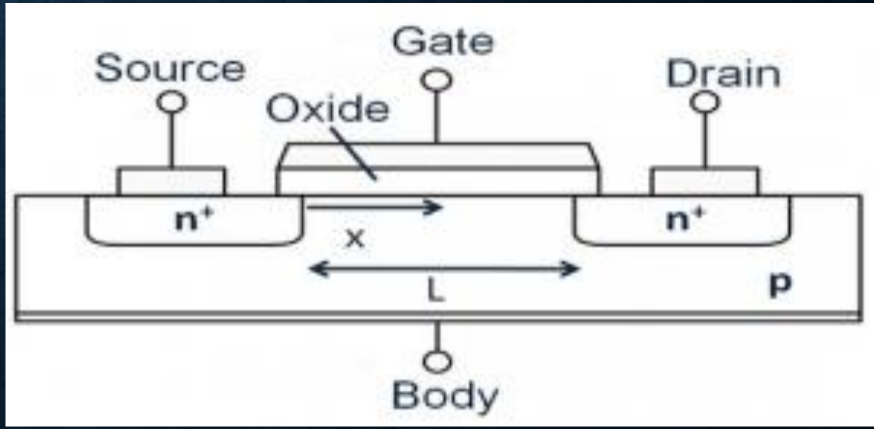
MOSFET-WORKING PRINCIPLE

- Main principle of the MOSFET device is to be able to control the voltage and current flow between the source and drain terminals. It works almost like a switch and the functionality of the device is based on the MOS capacitor. The MOS capacitor is the main part of MOSFET.

- Semiconductor surface at the below oxide layer which is located between the source and drain terminal can be inverted from p-type to n-type by the application of either a positive or negative gate voltages respectively. When we apply a repulsive force for the positive gate voltage, then the holes present beneath the oxide layer are pushed downward with the substrate.

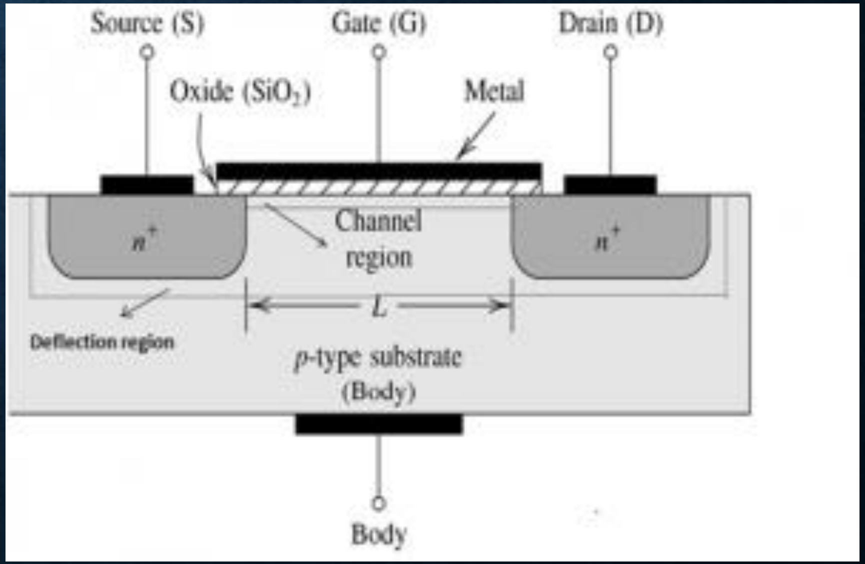
MOSFET

- Functionality of MOSFET depends on the electrical variations happening in the channel width along with the flow of carriers (either holes or electrons). The charge carriers enter into the channel through the source terminal and exit via the drain.
- The width of the channel is controlled by the voltage on an electrode which is called the gate and it is located in between the source and the drain. It is insulated from the channel near an extremely thin layer of metal oxide. The MOS capacity that exists in the device is the crucial section where the entire operation is across this.



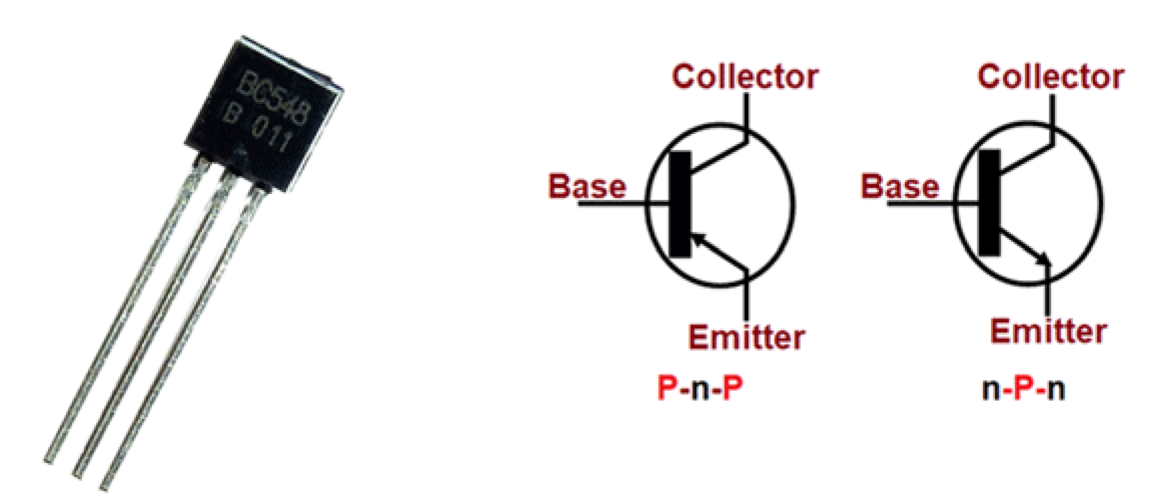
MOSFET-WORKING PRINCIPLE

- The depletion region populated by the bound negative charges which are associated with the acceptor atoms. When electrons are reached, a channel is developed. The positive voltage also attracts electrons from the n+ source and drain regions into the channel. Now, if a voltage is applied between the drain and source, the current flows freely between the source and drain and the gate voltage controls the electrons in the channel. Instead of the positive voltage, if we apply a negative voltage, a hole channel will be formed under the oxide layer.



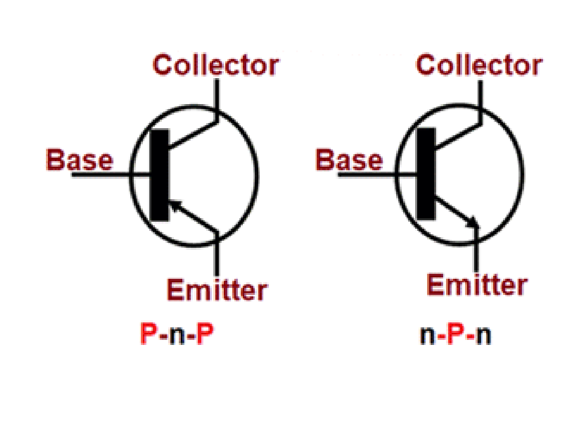
BJT-BIPOLAR JUNCTION TRANSISTOR

- BJT - Bipolar Junction Transistor, a solid-state current-controlled device which can be used to electronically switch a circuit
- BJT is a three-terminal device with an Emitter, collector, and a base pin
- Current flow through the emitter and collector are controlled by the amount of current applied to the base.
- Emitter and collector as the two ends of your switch and instead of pressing the switch, we have the base pin which can receive the control signal.



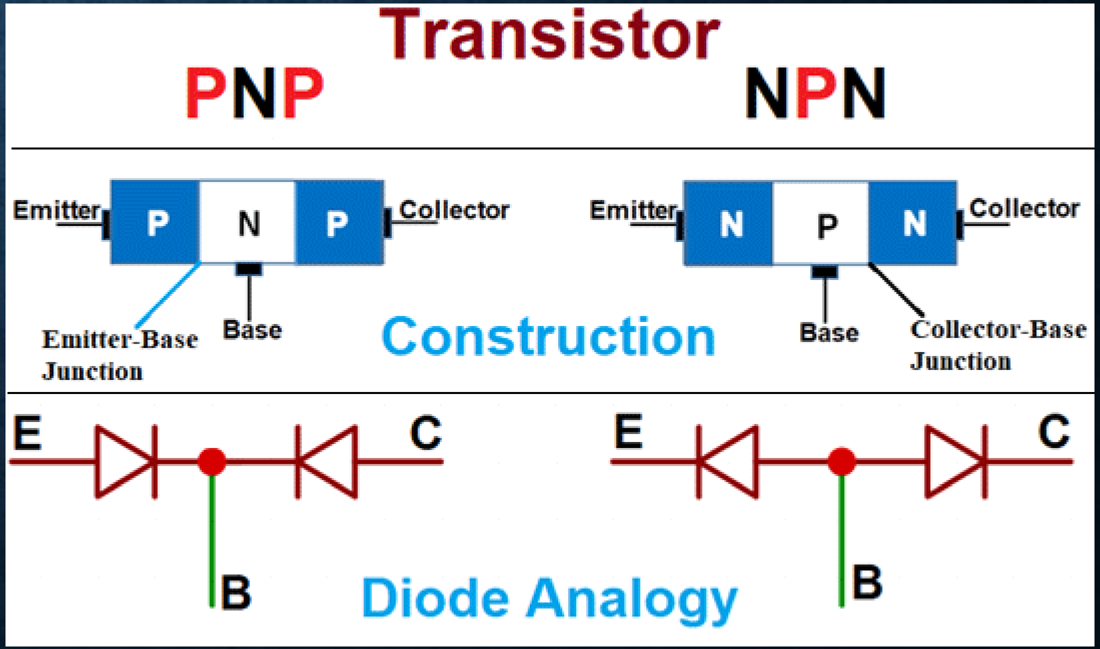
BJT-BIPOLAR JUNCTION TRANSISTOR

- Difference between PNP and NPN transistors is that the arrow mark at the emitter end if you have noticed
- Arrow in PNP transistor is mentioned as moving from the emitter to the base whereas in the NPN transistor the arrow will be moving from the base to the emitter.
- Direction of the arrow represents the direction of current flow in the transistor, in PNP the current will be flowing from emitter to base, similarly in the NPN transistor current will be flowing from the base to emitter.



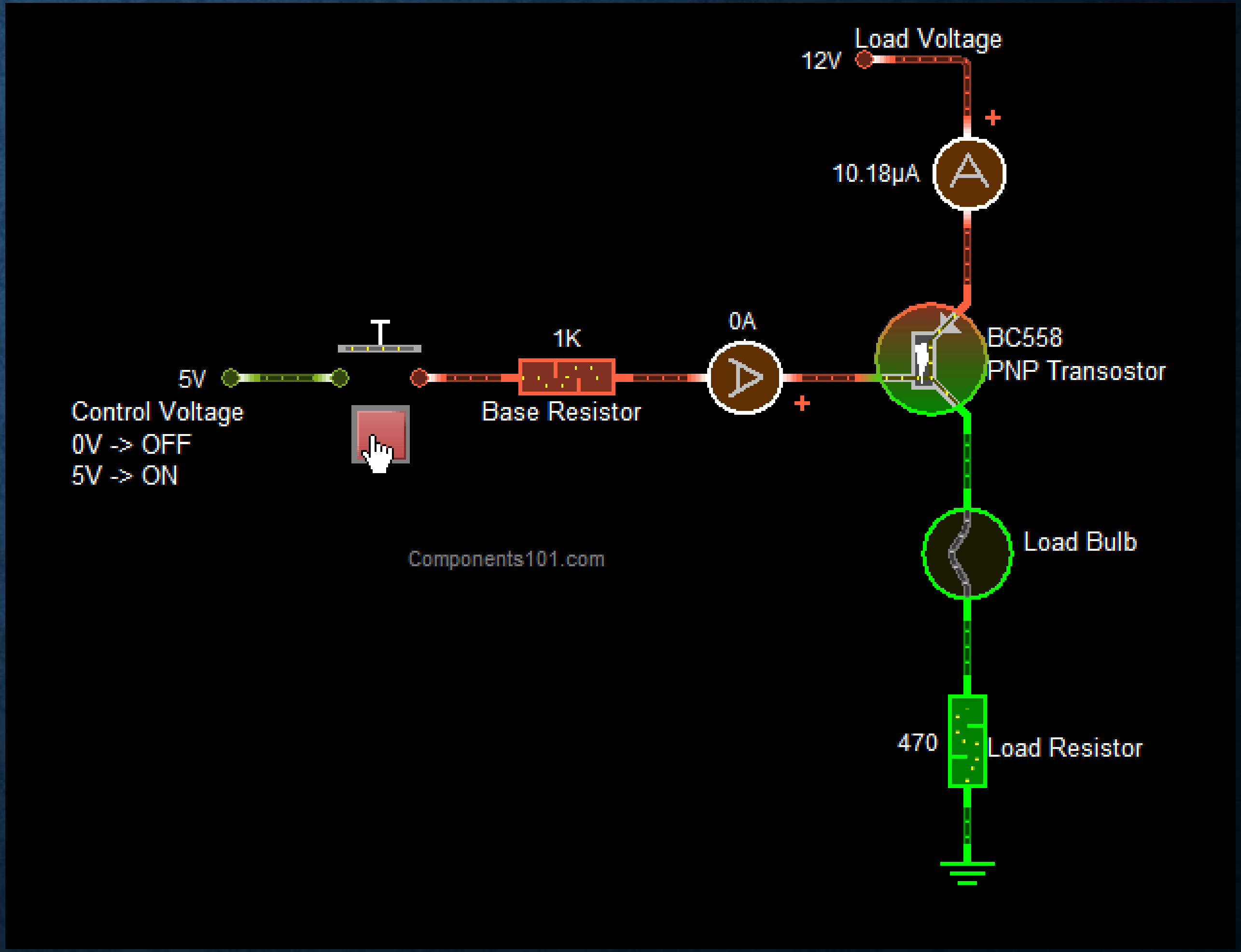
BJT-BIPOLAR JUNCTION TRANSISTOR

- BJT is formed by three layers of semiconductor materials, if it is a PNP transistor, it will have two P-type regions and one N-type region
- NPN transistor, will have two N-type regions and one P-type region.
- Two outer layers are where the collector and emitter terminals are fixed and the base terminal is fixed at the center layer.



BJT-BIPOLAR JUNCTION TRANSISTOR

- Can be used as a switch or as an amplifier.
- When a control voltage is provided to base, required base current (I_B) flows into base pin which is controlled by a base resistor.
- This current turns on the transistor (switch is closed) and allows the current to flow from collector to emitter. we are using a low-level voltage like 5V to drive a higher voltage load of 12V using this transistor.



DIODES

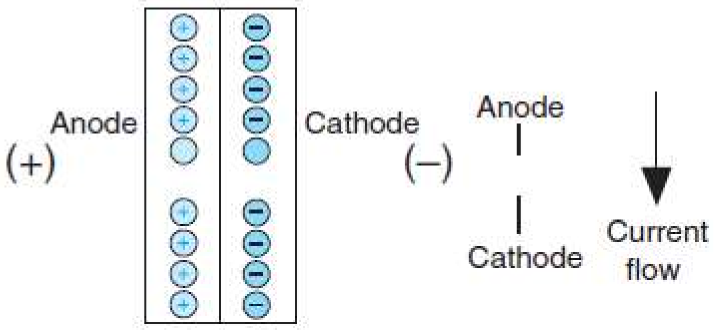
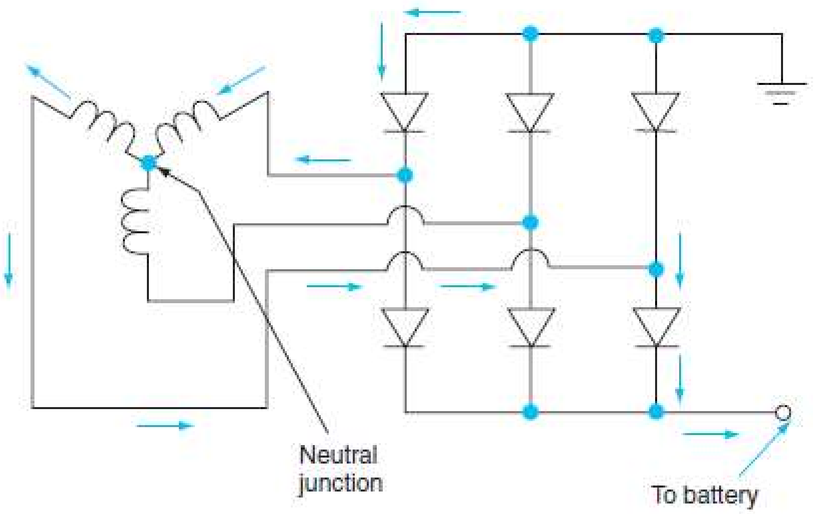


Figure The basic construction, electrical symbol, and direction of current flow of a diode.

- Diode is a simple semiconductor.
- Most commonly used are regular diodes, light emitting diodes (LEDs), zener diodes, clamping diodes, and photo diodes.
- Diode allows current to flow in one direction; therefore, it can serve as a conductor or insulator, depending on the direction of current flow. In an AC generator, voltage is rectified to DC by diodes.



Diodes are used to change the AC voltage from a generator into DC.

- Diodes are arranged so that current can leave the AC generator in one direction only (as direct current).
- Inside a diode are positive and negative areas that are separated by a boundary area called PN junction.
- When the positive side of a diode is connected to the positive side of the circuit, it is said to have forward bias.
- Unlike electrical charges are attracted to each other and like charges repel each other.
- Therefore, the positive charge from the circuit is attracted to the negative side.
- The circuit's voltage is much stronger than the charges inside the diode, which causes the diode's charges to move.
- Diode's P material is repelled by the positive charge of the circuit and is pushed toward the N material and the N material is pushed toward the P.
- This causes the PN junction to become a conductor, allowing current to flow.
- When reverse bias is applied to the diode, the P and N areas are connected to opposite charges.

- Since opposites attract, the P material moves toward the negative part of the circuit and the N material moves toward the positive part of the circuit.
- This empties the PN junction, and current flow stops.

ZENER DIODE

- A zener diode works like a standard diode until a certain voltage is reached.
- When the voltage reaches this point, the diode allows current to flow in the reverse direction.
- Zener diodes are often used in electronic voltage regulators.

LED

- LEDs emit light as current passes through them.
- Color of the emitted light depends on the material used to make the LED.
- Typically, LEDs are made from a variety of inorganic semiconductor materials that produce different colors.

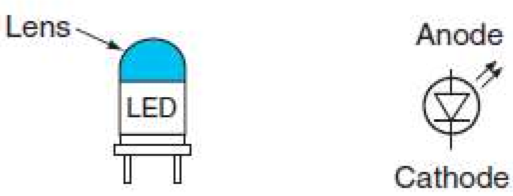


Figure An LED and its electrical symbol.

CLAMPING DIODE

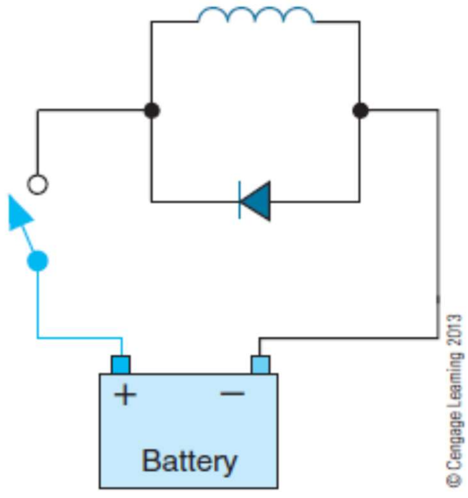


Figure 2-26 A clamping diode is connected in parallel with a coil to prevent voltage spikes that normally occur when the switch is opened.

- Whenever the current flow through a coil of wire (such as that used in a solenoid or relay) stops, a voltage surge or spike is produced.
- This surge results from the collapsing of the magnetic field around the coil.
- The movement of the field across the winding induces a very high voltage spike, which can damage electronic components.
- In the past, a capacitor was used as a ‘‘shock absorber’’ to prevent component damage from this surge.
- On today’s vehicles, a clamping diode is commonly used to prevent this voltage spike.
- Installing a clamping diode in parallel with the coil provides a bypass for the electrons during the time the circuit is opened.

IGBT

- An IGBT is a transistor which is produced by joining three sections of semiconductor materials.
- Like the diode, it is used as a switching amplifying device, functioning as either a conductor or an insulator.

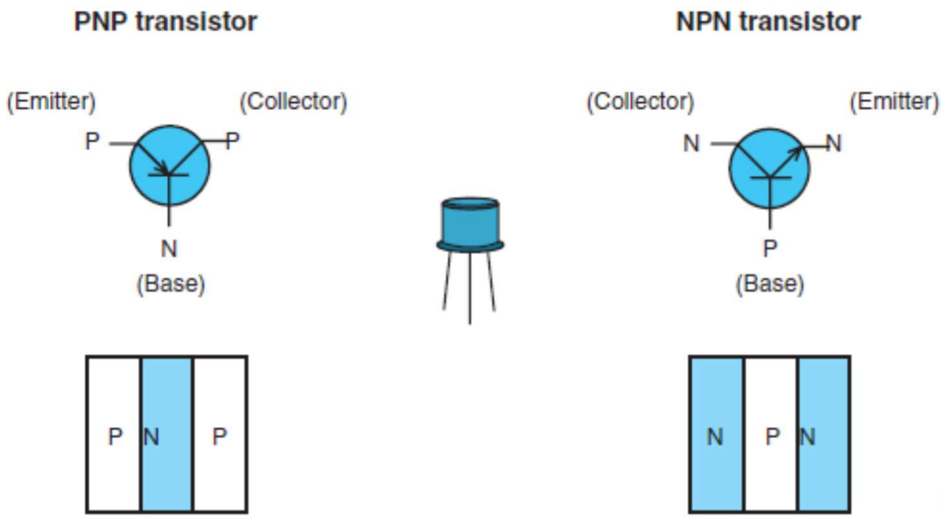


Figure 2-27 PNP and NPN transistors.

- A transistor resembles a diode with an extra side.
- It can consist of two P-type materials and one N-type material or two N-type materials and one P-type material. These are called PNP and NPN types.
- In both types, junctions occur where the materials are joined. Each of the three sections has a lead connected to it.
- This allows any of the three sections to be connected to the circuit. Legs are the emitter, base, and collector.

- The center section is called the base and is the controlling part of the circuit or the place where the larger controlled part of the circuit is switched.
- Path to ground is through the emitter.
- Resistor is normally in the base circuit to keep current flow low. This prevents damage to the transistor.
- Emitter and collector make up the control circuit.
- When a transistor is drawn in an electrical schematic, there is an arrow on the emitter. Current always flows against the arrow.
- Base of a PNP transistor is controlled by its ground. Current flows from the emitter through the base, then to ground.
- Negative voltage or ground must be applied to the base to turn on a PNP transistor.
- When the transistor is on, the circuit from the emitter to the collector is complete.
- NPN transistor is the opposite of a PNP. When positive voltage is applied to the base of an NPN transistor, the collector-to-emitter circuit is turned on.

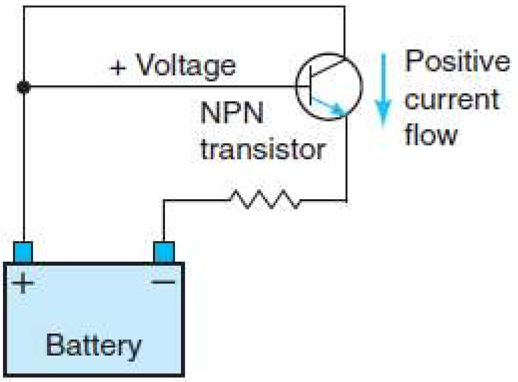


Figure 2-28 When the base is forward biased with a more positive voltage, the collector-to-emitter circuit is turned on.

- Transistors can also function as variable switches.
- When completeness of the emitter and collector circuit will also vary. This is done simply by the presence of a variable resistor in the base circuit.
- This principle is used in light-dimming circuits.
- A transistor commonly used in the control circuit of electric drive vehicles is the insulated gate bipolar transistor (IGBT).
- This is a high-current transistor.
- Single IGBT can handle large amounts of current. They most often are liquid cooled to control the heat generated by the high current.

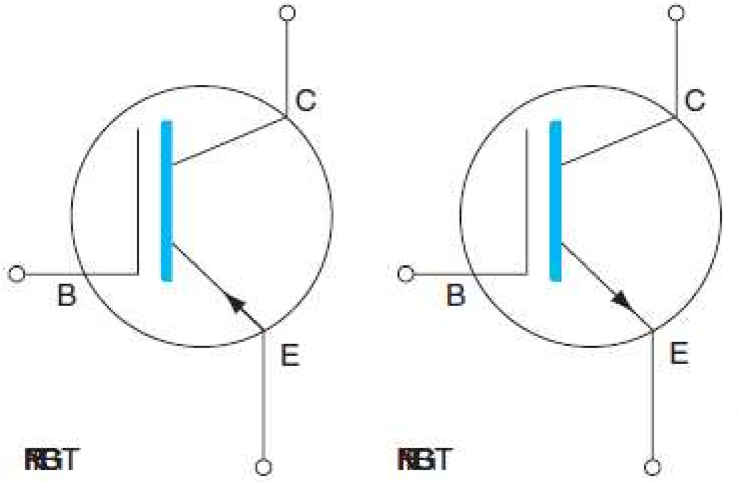


Figure 2-29 The electrical symbols for a PNP and NPN

INVERTERS AND CONVERTERS

- An inverter may be part of the controller or it may be a separate unit.
- Inverter converts the DC voltage from the batteries into three phase AC voltage for the motor(s).
- DC voltage from the battery is fed to the primary winding of a transformer in the inverter.

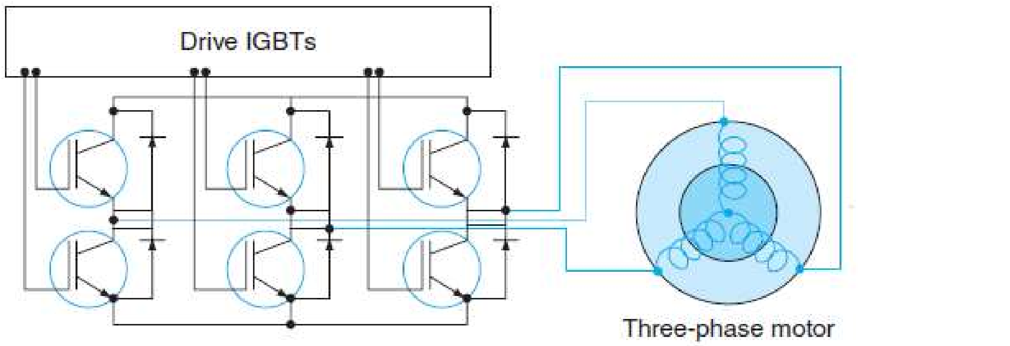


Figure 3-38 An electrical diagram of the connections made from the motor to the IGBTs in an inverter.

- Direction of the current is controlled by an electronic switch (generally a set of insulated gate bipolar transistors primary winding and then is quickly stopped and reverses its direction.
- This change of direction induces an AC voltage in the transformer's secondary winding.
- AC is then used to power the traction motors and other AC devices.
- Electronic switch responds to inputs from a variety of sensors, such as vehicle speed and throttle position.
- These inputs are used to determine the required amount of current and the frequency of the AC voltage.
- When the conversion of AC to DC is required, current is sent through diodes that effectively change AC to DC by allowing only half of the AC's sine wave to flow past the diodes.
- Diodes are normally called rectifiers. Rectifiers are also found in AC generators.
- Most inverter housings also contain a converter, although this could be contained in a separate housing.
- A converter changes the amount of voltage from a power source.
- Two types of converters, one that increases voltage, called a step-up converter, and one that decreases the voltage, called a step-down converter.

- Common application of a converter in electric drive vehicles is one that drops some of the high DC voltage to the low voltage required to power accessories such as sound systems, lights, blower fans & controller.
- Converter is also used to step down (reduce) high AC voltage to power accessories such as the air-conditioning compressor.
- During the operation of the inverter and converter, a great amount of heat is generated.
- This heat must be controlled to protect their components, especially the transistors.
- To provide the necessary cooling and ventilation, inverter/converter housings have dedicated cooling systems that are independent of the engine's cooling system.

Figure 3-37 The inverter assembly for a Toyota hybrid vehicle.

DC/DC CONVERTERS FOR ELECTRIC VEHICLES

ELECTRIC VEHICLES POWERTRAIN

- An Electric Vehicle is a vehicle that uses a combination of different energy sources, Fuel Cells (FCs), Batteries and Supercapacitors (SCs) to power an electric drive system as shown in Fig.
- In EV the main energy source is assisted by one or more energy storage devices. Thereby the system cost, mass, and volume can be decreased, and a significant better performance can be obtained.
- Two often used energy storage devices are batteries and SCS.
- They can be connected to the fuel cell stack in many ways. A simple configuration is to directly connect two devices in parallel, (FC/battery, FC/SC, or battery/SC).
- However, in this way the power drawn from each device cannot be controlled, but is passively determined by the impedance of the devices.
- The impedance depends on many parameters, e.g. temperature, state-of-charge, health, and point of operation. Each device might therefore be operated at an inappropriate condition, e.g. health and efficiency.
- The voltage characteristics also have to match perfectly of the two devices, and only a fraction of the range of operation of the devices

can be utilized, e.g. in a fuel cell battery configuration the fuel cell must provide almost the same power all the time due to the fixed voltage of the battery.

- In a battery/supercapacitor configuration only a fraction of the energy exchange capability of the supercapacitor can be used. This is again due to the nearly constant voltage of the battery.
- By introducing DC/DC converters one can chose the voltage variation of the devices and the power of each device can be controlled

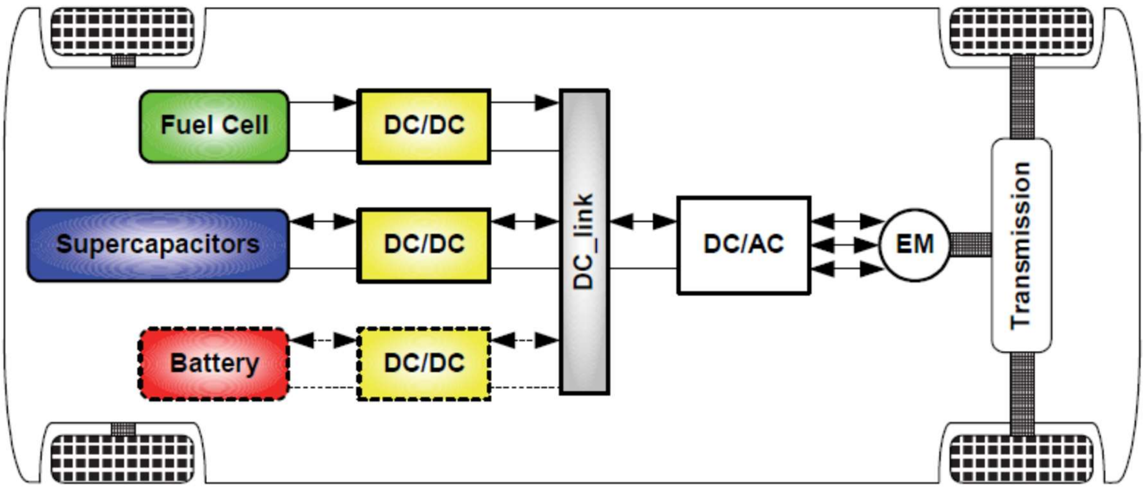


Fig. 1. Electric vehicle drive system.

- Use of high-power DC/DC converters is necessary for EV power supply system.
- The power of the DC/DC converter depends on the characteristics of the vehicle such as top speed, acceleration time from 0 to 100 Km/h, weight, maximum torque, and power profile (peak power, continuous power).

- Generally, for passenger cars, the power of the converter is more than 20 KW and it can go up to 100 KW.

DC/DC converters for electric vehicles

- DC/DC converters can be designed to transfer power in only one direction, from the input to the output.
- However, almost all DC/DC converter topologies can be made bi-directional.
- A bi-directional converter can move power in either direction, which is useful in applications requiring regenerative braking.
- The amount of power flow between the input and the output can be controlled by adjusting the duty cycle (ratio of on/off time of the switch).
- Usually, this is done to control the output voltage, the input current, the output current, or to maintain a constant power.
- The main drawbacks of switching converters include complexity, electronic noise and high cost for some topologies.
- Common DC/DC converters can be grouped as follows:

Non-isolated converters

- Non-isolated converters type is generally used where the voltage needs to be stepped up or down by a relatively small ratio (less than 4:1).

- There are five main types of converter in this non-isolated group, usually called the buck, boost, buck-boost, Cuk and charge-pump converters.
- The buck converter is used for voltage step-down, while the boost converter is used for voltage step-up.
- The buck-boost and Cuk converters can be used for either stepdown or step-up.
- The charge-pump converter is used for either voltage step-up or voltage inversion, but only in relatively low power applications.

Isolated converters

- Usually, in this type of converters a high frequency transformer is used. In the applications where the output needs to be completely isolated from the input, an isolated converter is necessary.
- Many types of converters in this group such as Half-Bridge, Full-Bridge, Fly-back, Forward and Push-Pull DC/DC converters.
- All of these converters can be used as bi-directional converters and the ratio of stepping down or stepping up the voltage is high.

Electric vehicle converters requirements

- Light weight,
- High efficiency,
- Small volume,

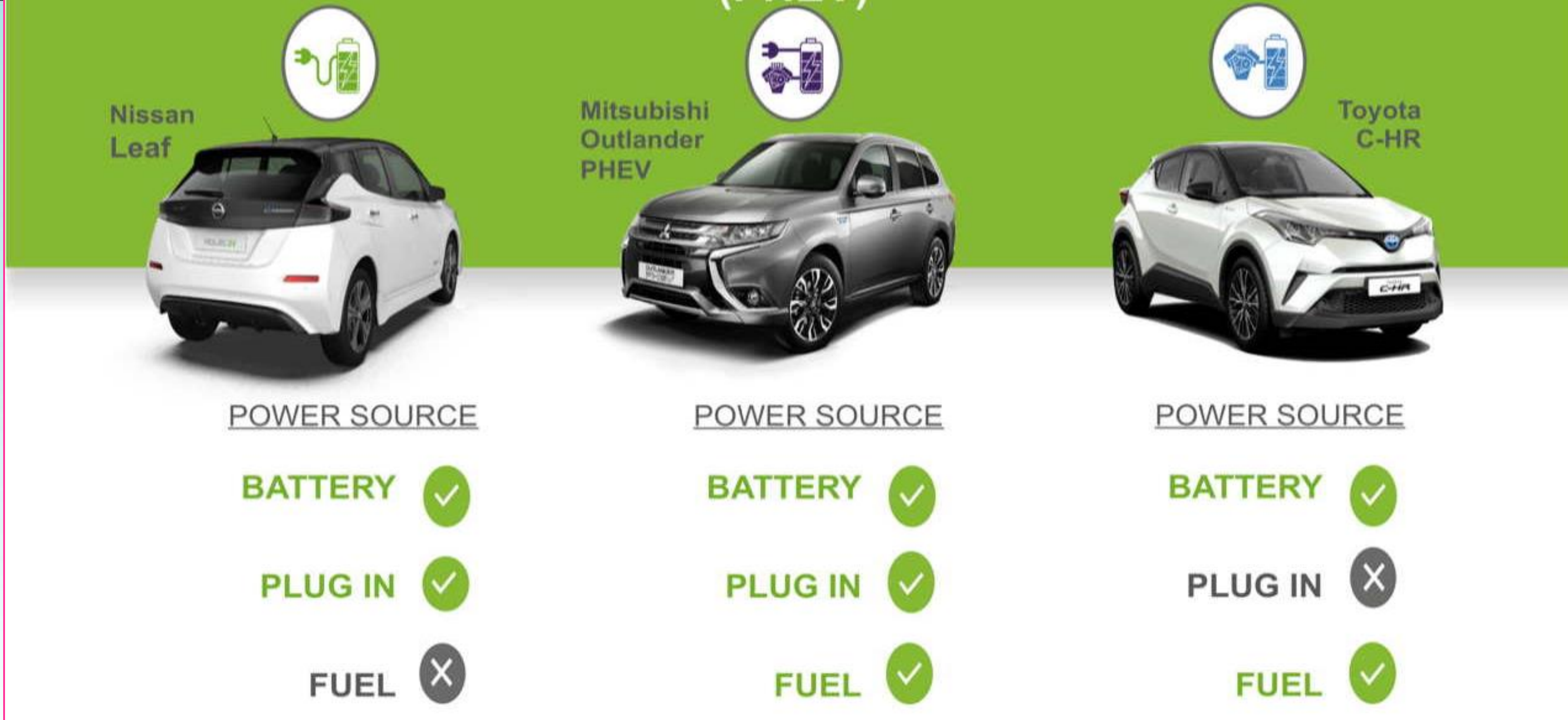
- Low electromagnetic interference,
- Low current ripple drawn from the Fuel Cell or the battery,
- The step-up function of the converter,
- Control of the DC/DC converter power flow subject to the wide voltage variation on the converter input.

HYBRID ELECTRIC VEHICLE (HEV)

Dr. S. ARUMUGAM
Associate Prof./Mech. Engg.
SCSVMV

PRESENTATION OUTLINE

- What is HEV?
- Introduction
- Types of HEV
- Architecture of HEV
- Advantages of HEV
- Disadvantages of HEV



Nissan Leaf
Mitsubishi Outlander PHEV
Toyota C-HR
POWER SOURCE
BATTERY
PLUG IN
FUEL
POWER SOURCE
BATTERY
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FUEL
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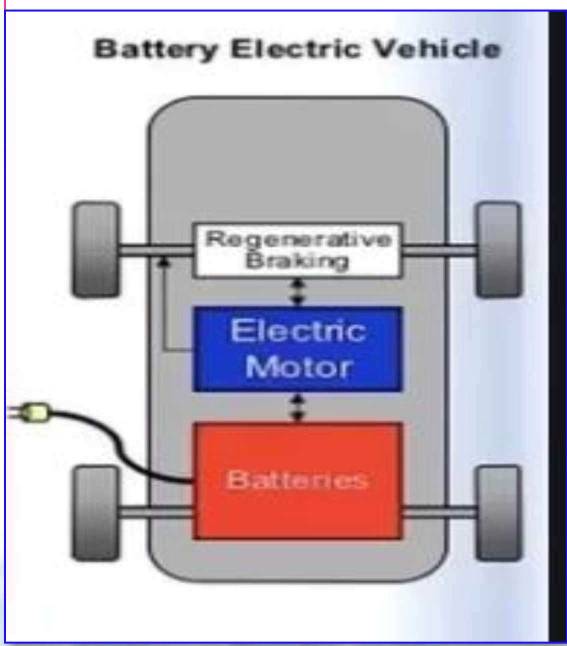
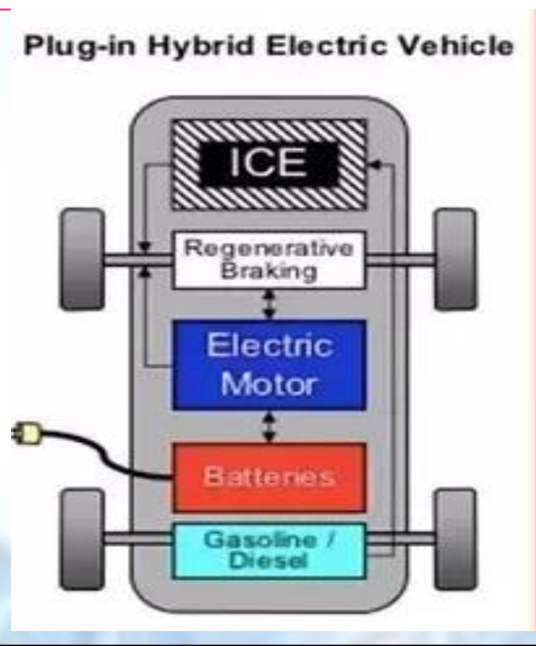
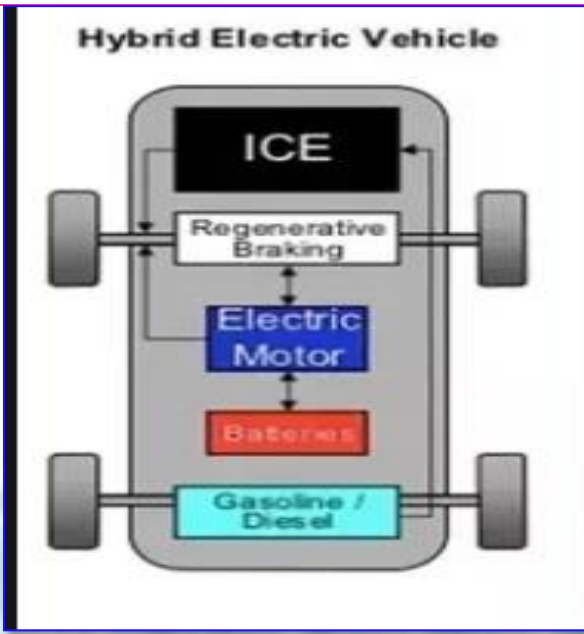
BATTERY
PLUG IN
FUEL



Battery Electric Vehicle
Regenerative Braking
Electric Motor
Batteries



Plug-in Hybrid Electric Vehicle
ICE
Regenerative Braking
Electric Motor
Batteries
Gasoline / Diesel



Hybrid Electric Vehicle
ICE
Regenerative Braking
Electric Motor
Gasoline / Diesel

HYBRID ELECTRIC VEHICLES (HEV)

Figure 1.4 Toyota Prius – HEV (Source: Toyota Media)

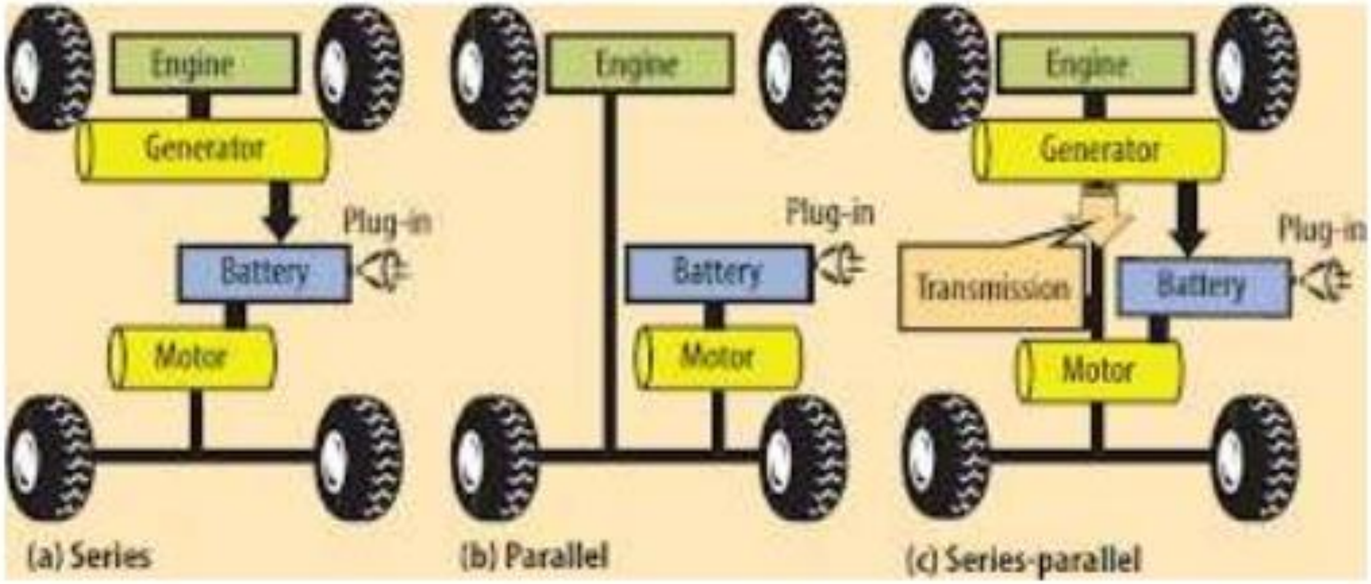
- **Vehicle powered by battery and/or ICE.**
- **Power source is selected automatically by the vehicle, depending on speed, engine load & battery charge.**
- **Battery cannot be plugged in, so charge is maintained by regenerative braking supplemented by ICE-generated power.**

HYBRID ELECTRIC VEHICLES (HEV)

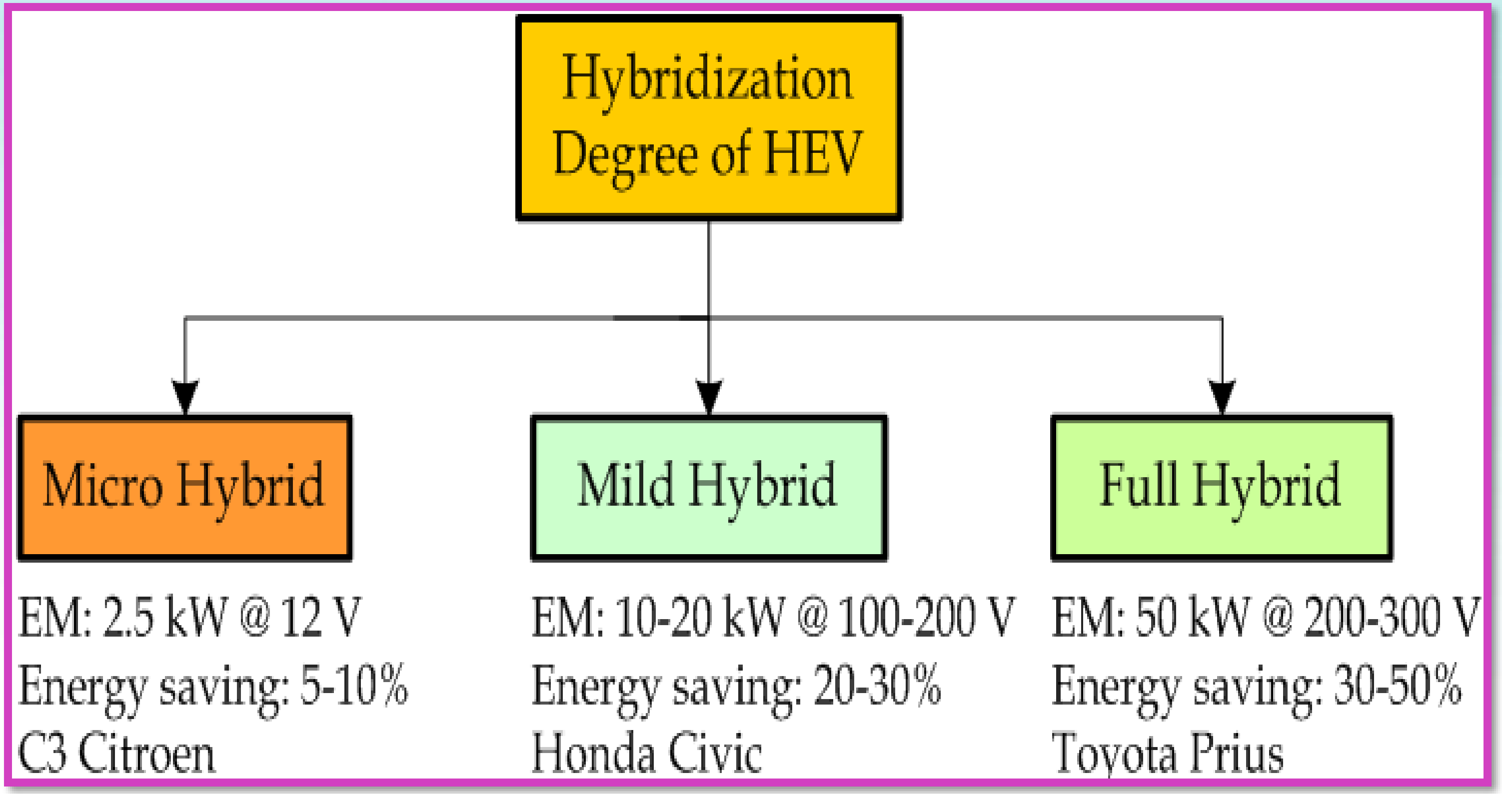
- HEVs are electric drive vehicles combine the technologies of BEVs & ICEVs.
- HEVs Designed to take advantage of ICEV & BEVs.
- HEVs use smaller ICE & electric motor to provide power for acceleration & overcoming loads.
- Power from electric motor supplements the engine's power.
- There is also improvement in highway fuel mileage, because of the use of smaller & more efficient engines.

HEV - TYPES

- Based on configuration of the vehicle drivetrain -
  - Series Hybrid
  - Parallel Hybrid
  - Series – Parallel Hybrid



HEV TYPES

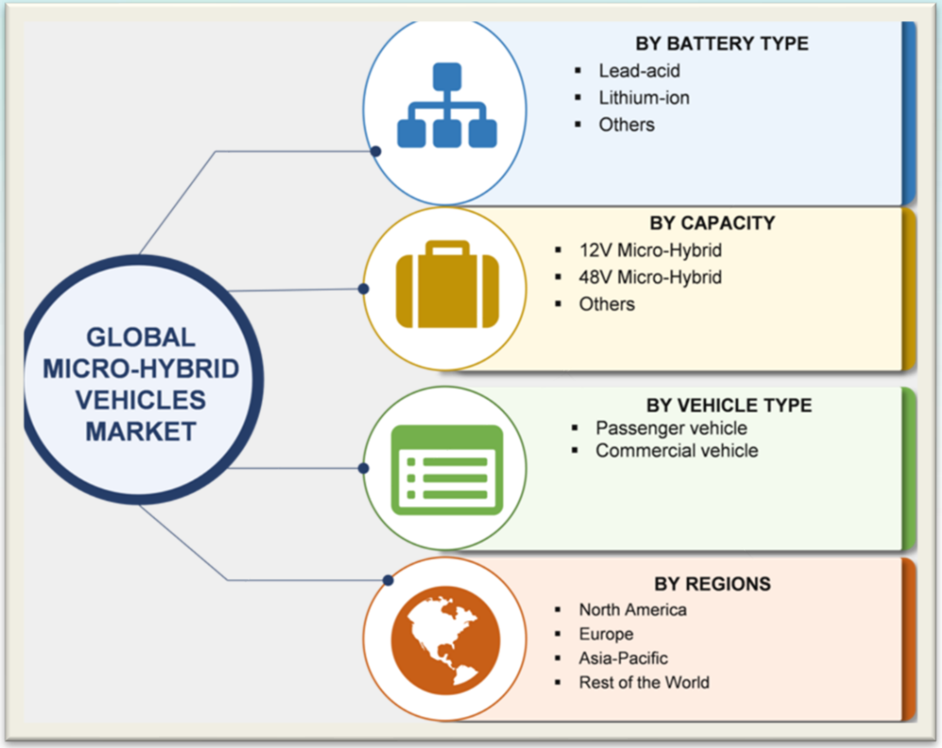


Degree of Hybridization <5% **Upto 10 %** **Upto 75 %**

DEGREE OF HYBRIDIZATION

- Ratio of power developed by an electric motor in a hybrid vehicle to the total power consumed by vehicle is known as degree of hybridization.
- Degree of hybridization depends upon power supplied by ICE & electric motor.
- Some vehicles, ICE is dominant; electric motor turns on only when boost is needed.
- Many vehicles, both ICE & electric motor share equal loads.
- Degree of hybridization = $\frac{Motor\ Power}{Motor\ Power + Engine\ Power}$ x 100

MICRO HYBRID

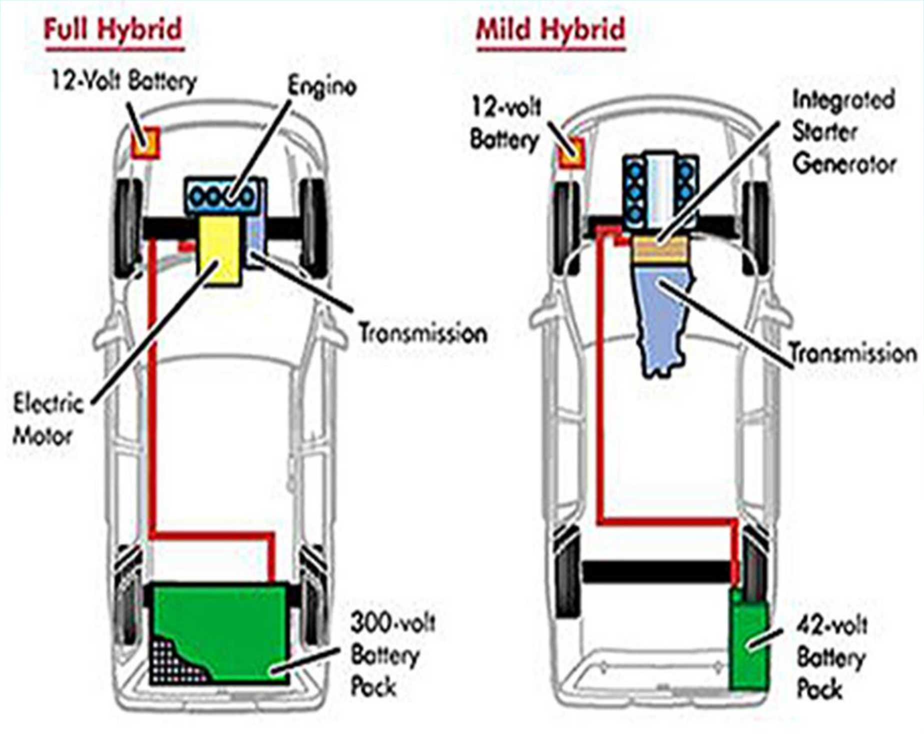


- Electric motor functions to start or stop the system to automatically shut off engine @ idling.
- Motor doesn't provide additional torque to vehicle.
- Motor power: 2.5 kW @12V.
- Energy saving: 5-10%.

Ex: BMW 1 series

Fortwo Mercedes & etc.

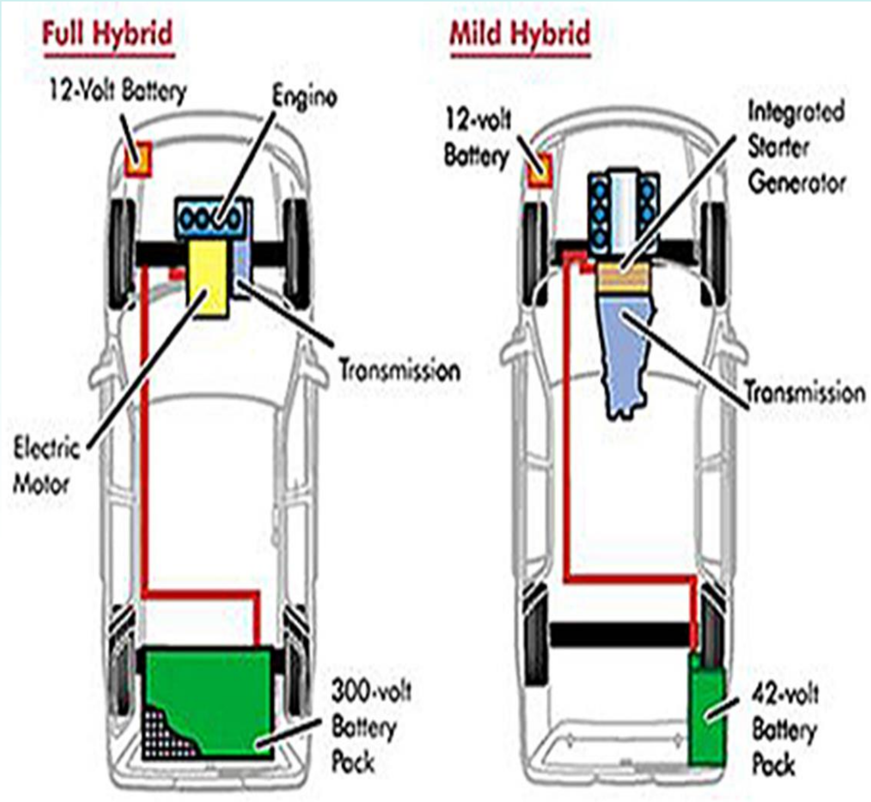
MILD HYBRID



- Electric motor is integrated to provide 10% of maximum engine power.
- Hybrids improve drawbacks of fossil fuel vehicles.
- Motor or generator is in parallel with ICE.
- Motor power: 10-20kW@ 100-200 V.
- Energy saving: 20-30%

Ex: Chevrolet Malibu

FULL HYBRID



- Electric motor provides at least 40% of engine power as additional torque.
- Bigger motor and battery reduces the required size of ICE.
- Improved fuel consumption and reduced emissions.
- Motor Power:50kW@200-300 V.
- Energy saving: 30-50%

Ex: Toyota Prius, KIA & FORD-FUSION

HEV – TYPES: BASED ON POWER SOURCE

- **Electric motor-ICE hybrid vehicle**
- **Fuel cell hybrid vehicle**
- **Hydraulic hybrid vehicle**
- **Pneumatic hybrid vehicle**
- **Solar Powered hybrid vehicle**
- **Flex fuel hybrid vehicle**

HEV – TYPES: Based on Power Source

Electric IC Engine hybrid	Fuel cell hybrid	Hydraulic hybrid	Pneumatic hybrid	Human & environmental power hybrid	Flex fuel hybrid vehicle
Types are Series & parallel	Series hybrid combination	Uses hydraulic & mechanical components	Compressed air & electric motors are used	Types are series & parallel Solar cells, battery& pedals are used	Gasoline & ethanol E85 or natural gas are used
Motor acts as a generator	Fuel cell (hydrogen) & electric motor used	Hydraulic Accumulator & variable displacement pump is used	Braking energy is stored to assist engine	Solar cells , battery operated motors & pedals are used	CNG or LPG can be used along with gasoline
Less life & less efficiency	Less size	More efficient system	More efficient	Less efficiency	More efficient
Cheaper system	Less cost	Cheaper & durable system	Cheaper system	Costly system	Cheaper system
Less space required	Less space required	More space required	More space required	More space required	More space required
Very popular , used a lot	Rarely used	Used in Volvo Buses since 1980	Air cars are produced in France	Used in motorcycles	4 million vehicles are working

ARCHITECTURE OF HEV

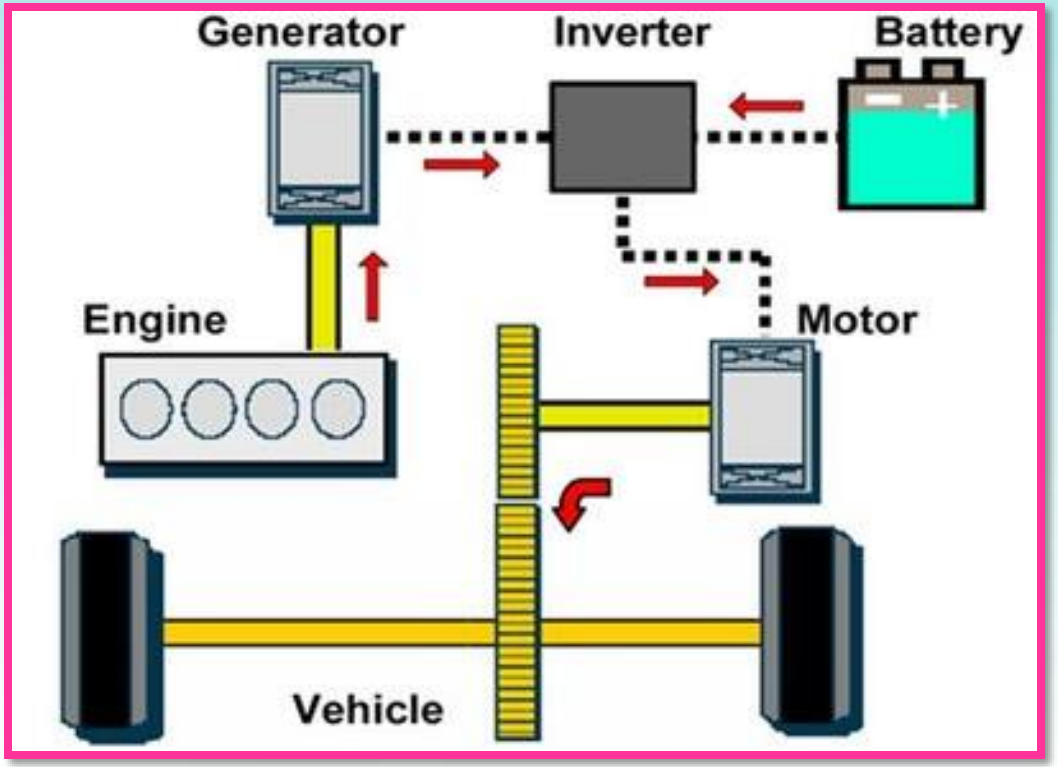
- **HEV uses both ICE & electric motor/generator for propulsion.**

- **Two power devices, ICE & electric motor can be connected in series or in parallel or series-parallel.**

- **When ICE & motor are connected in series, the HEV is a series hybrid in which only electric motor is providing mechanical power to wheels.**

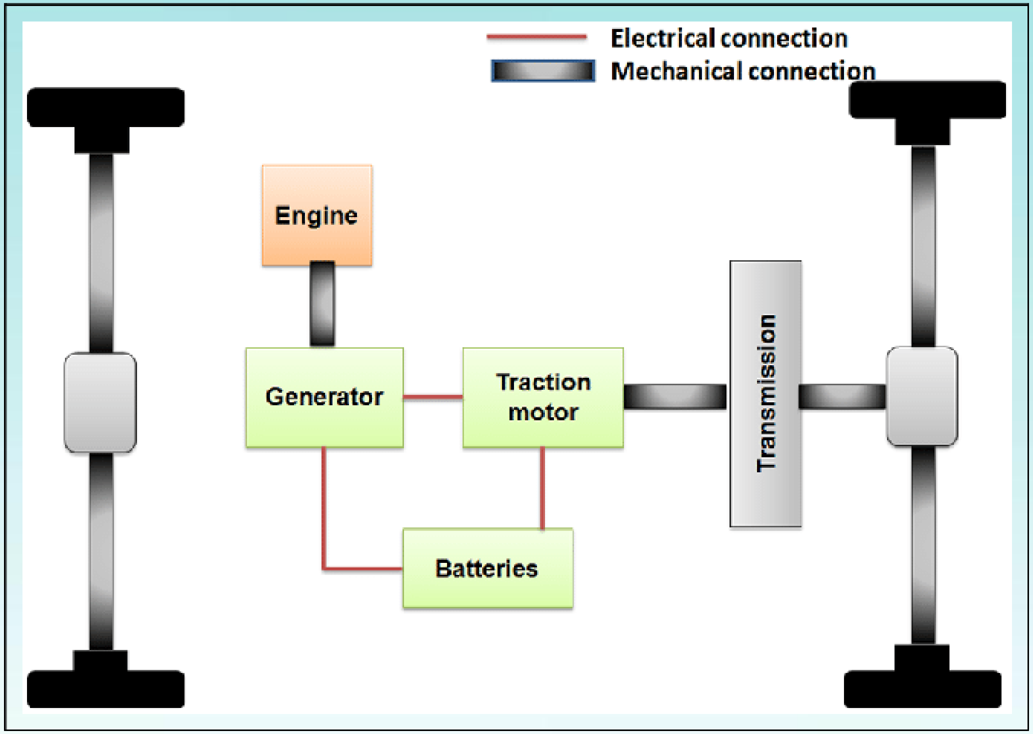
- **When ICE & electric motor are connected in parallel, the HEV is a parallel hybrid in which both electric motor & ICE can deliver mechanical power to wheels.**

ARCHITECTURE OF SERIES HEV



- ICE drives a generator. ICE converts energy in fuel to mechanical energy, and the generator converts mechanical energy of the engine output to electricity.
- Electric motor will propel the vehicle & also used to capture K.E. during braking (Regenerative).
- Battery between generator & electric motor to buffer the electric energy between I/G set motor.

SERIES HEV



- Electric motor can receive electricity directly from engine, or from battery, or both.
- As engine is decoupled from the wheels, engine speed can be controlled independently of vehicle speed.
- Good control of engine, allow the operation of engine at its optimum speed to achieve fuel economy.
- Provides flexibility in locating the engine on the vehicle.
- No need for the traditional mechanical transmission.

OPERATIONAL COMBINATIONS OF SERIES HEV

- **Battery alone: When battery has sufficient energy & vehicle power demand is low, the I/G set is turned off, and vehicle is powered by battery only.**

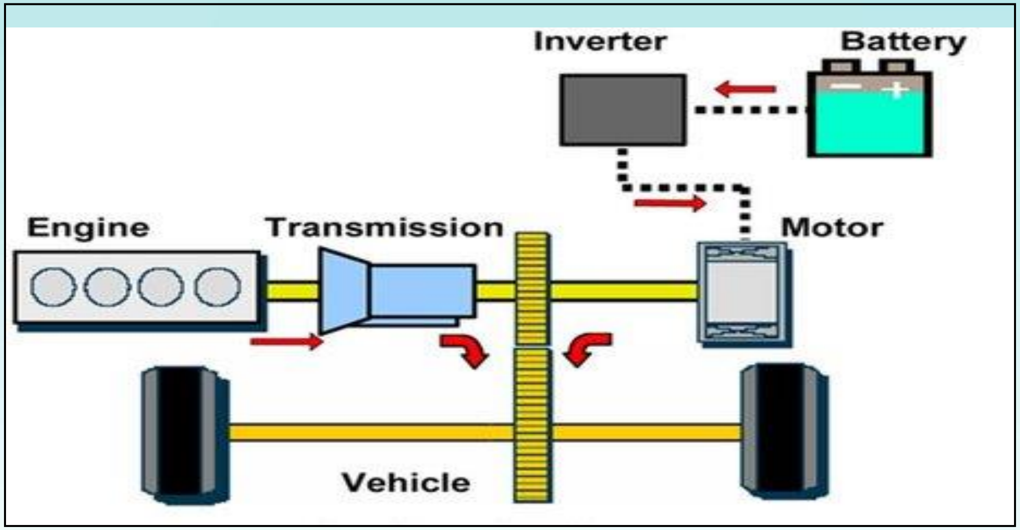
- **Combined power: At high power demands, I/G set is turned on & battery also supplies power to motor.**

OPERATIONAL COMBINATIONS OF SERIES HEV

- **Engine alone: During highway cruising, @ moderately high power demands, I/G set is turned on. Battery is neither charged nor discharged. This is due to the fact that battery's state of charge (SOC) is already at a high level but power demand of vehicle prevents engine from off or it may not be efficient to turn engine off.**

- **Power split: When I/G is turned on, vehicle power demand is below the I/G optimum power & battery SOC is low, then portion of I/G power is used to charge battery.**

ARCHITECTURE OF PARALLEL HEV

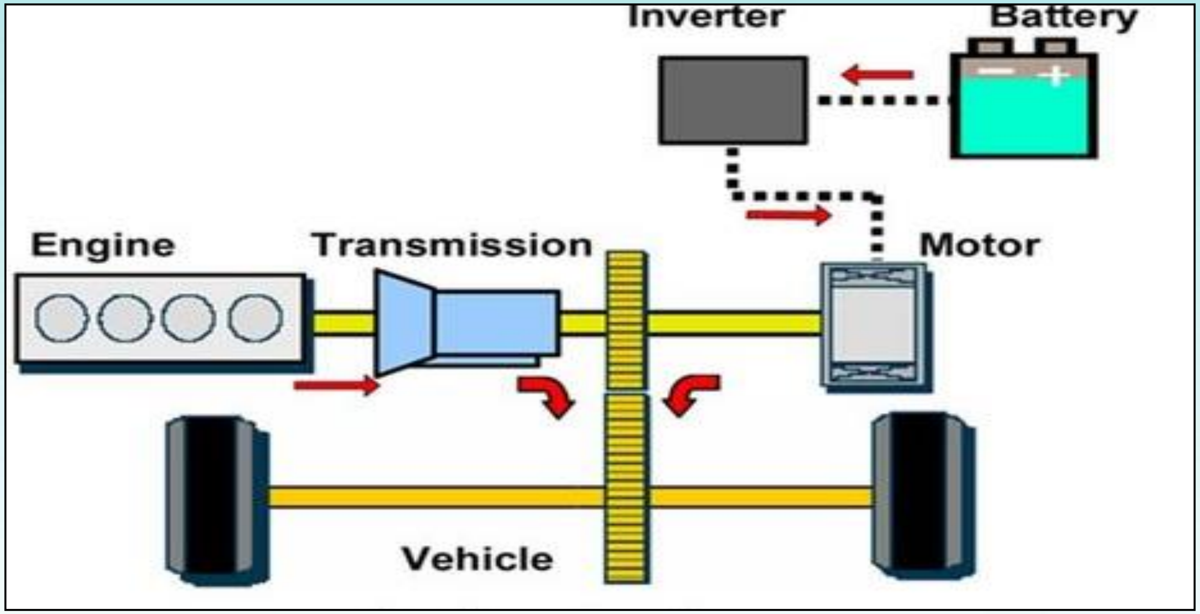


- **Parallel hybrid is one in which more than one conversion device can deliver propulsion power to the wheels.**

- **ICE & electric motor are configured in parallel with a mechanical coupling that blends the torque from two sources.**

- **Power requirements of electric motor are lower than electric vehicle or series hybrid; as ICE complements to total power demand of vehicle.**

ARCHITECTURE OF PARALLEL HEV



- **ICE and electric motor are coupled to final drive through a mechanism such as clutch, belt, pulley, & gears.**

- **Both ICE & motor can deliver power to the final drive, either in combined mode, or each separately.**

- **Electric motor can be used as a generator to recover the kinetic energy during braking or by absorbing a portion of power from ICE.**

OPERATIONAL COMBINATIONS OF PARALLEL HEV

- **Motor-alone mode: When battery has sufficient energy, and vehicle power demand is low, then engine is turned off and vehicle is powered by motor & battery only.**

- **Engine-alone mode: During highway cruising & moderately high power demands, the engine provides power needed to drive the vehicle. Motor remains idle due to the fact that battery SOC is already at a high level but the power demand of the vehicle prevents engine from turning off.**

- **Combined power mode: At high power demands, engine is turned on & motor also supplies power to the wheels.**

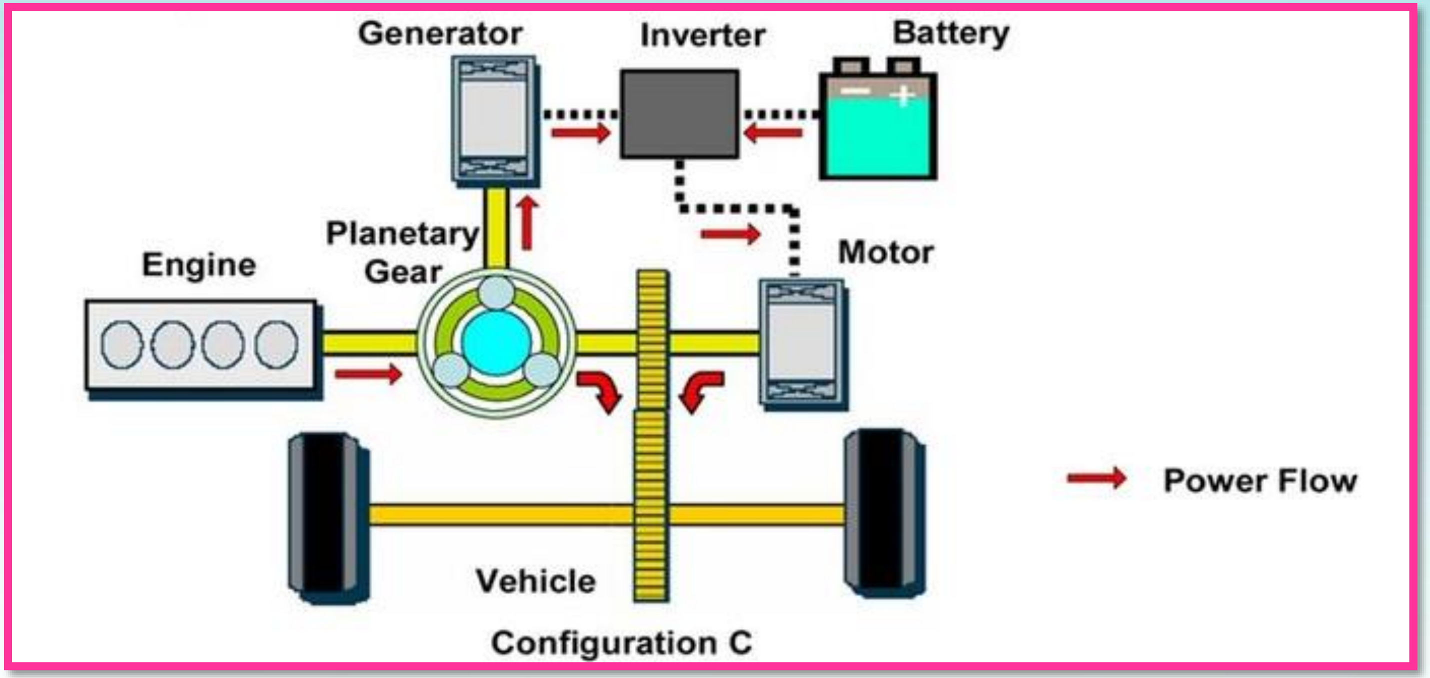
OPERATIONAL COMBINATIONS OF PARALLEL HEV

- **Power split mode: When engine is on, but vehicle power demand is low & battery SOC is also low, then a portion of the engine power is converted to electricity by motor to charge battery.**

- **Stationary charging mode: Battery is charged by running the motor as a generator and driven by the engine, without the vehicle being driven.**

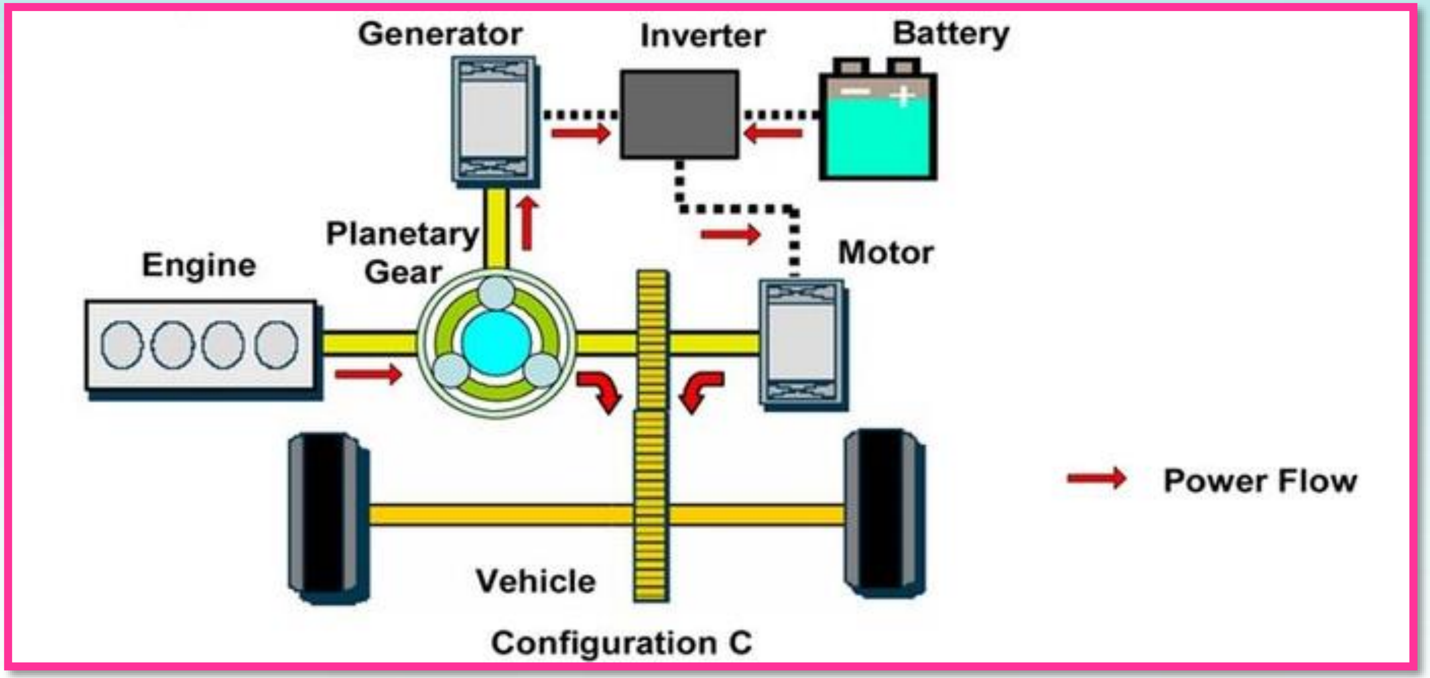
- **Regenerative braking mode: Electric motor is operated as a generator to convert vehicle's K.E into electric energy and store it in battery.**

ARCHITECTURE OF SERIES-PARALLEL HEV



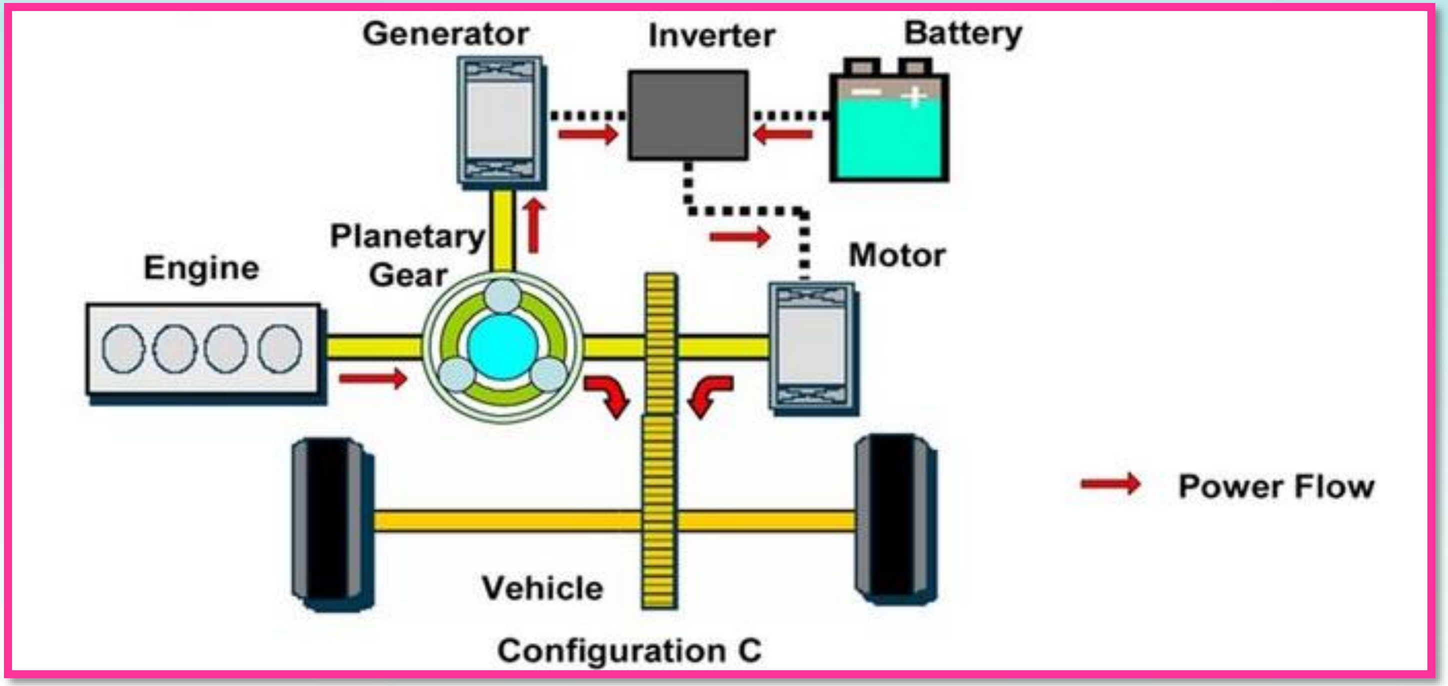
- In S-P hybrids, ICE is also used to charge battery.
- S-P HEV is series HEV, with a small series element added to architecture.
- Battery charge is sustained in prolonged wait period in traffic jam.
- Power split device allocated power from ICE to front wheels through driveshaft and electric generator.

ARCHITECTURE OF SERIES-PARALLEL HEV



- Incorporates the features of both series and parallel HEV.
- Can be operated as a series or parallel HEV.
- In comparison to a series HEV, series–parallel HEV adds a mechanical link between engine & final drive, so the engine can drive the wheels directly.
- As compared to a parallel HEV, series–parallel HEV adds a second electric machine that serves as generator.

ARCHITECTURE OF SERIES-PARALLEL HEV



- As series–parallel HEV can operate in both parallel and series modes, fuel efficiency and drivability can be optimized based on operating condition.
- Increased degree of freedom in control makes the series–parallel HEV a popular choice.
- Due to increased components and complexity, a series–parallel HEV is more expensive than series or parallel HEV.

HEV ADVANTAGES

- Regenerative Braking
- Reduction in engine & vehicle weight
- Fuel efficiency is increased
- Emissions are decreased
- Cut emissions of global warming pollutants by 1/3 or 1/2
- Reduce dependency on fossil fuels
- Some states offer incentives with owning an HEV
- ~2 times more efficient than conventional engines.

DISADVANTAGES OF HYBRID CARS

- Currently more expensive than conventional
- Heavier than conventional, due to battery pack and electric motors weight
- Limited battery life
- Expensive battery pack if you want to replace it
- Safety issues, high voltage battery and fuel
- Reliability, still under study,
- More complex computer controlled systems
- May have drivability issues
- Expensive to repair
- Towing Capacity

REGENERATIVE BRAKING

- **System that allows a vehicle to recapture and store part of K.E that would ordinarily be lost during braking.**

- **Vehicle has more kinetic energy when it is moving fast; therefore, regenerative braking is more efficient at higher speeds.**

- **When brakes are applied in a conventional vehicle, friction at the wheel brakes converts the vehicle's kinetic energy into heat.**

- **With regenerative braking, energy is used to recharge batteries.**

REGENERATIVE BRAKING

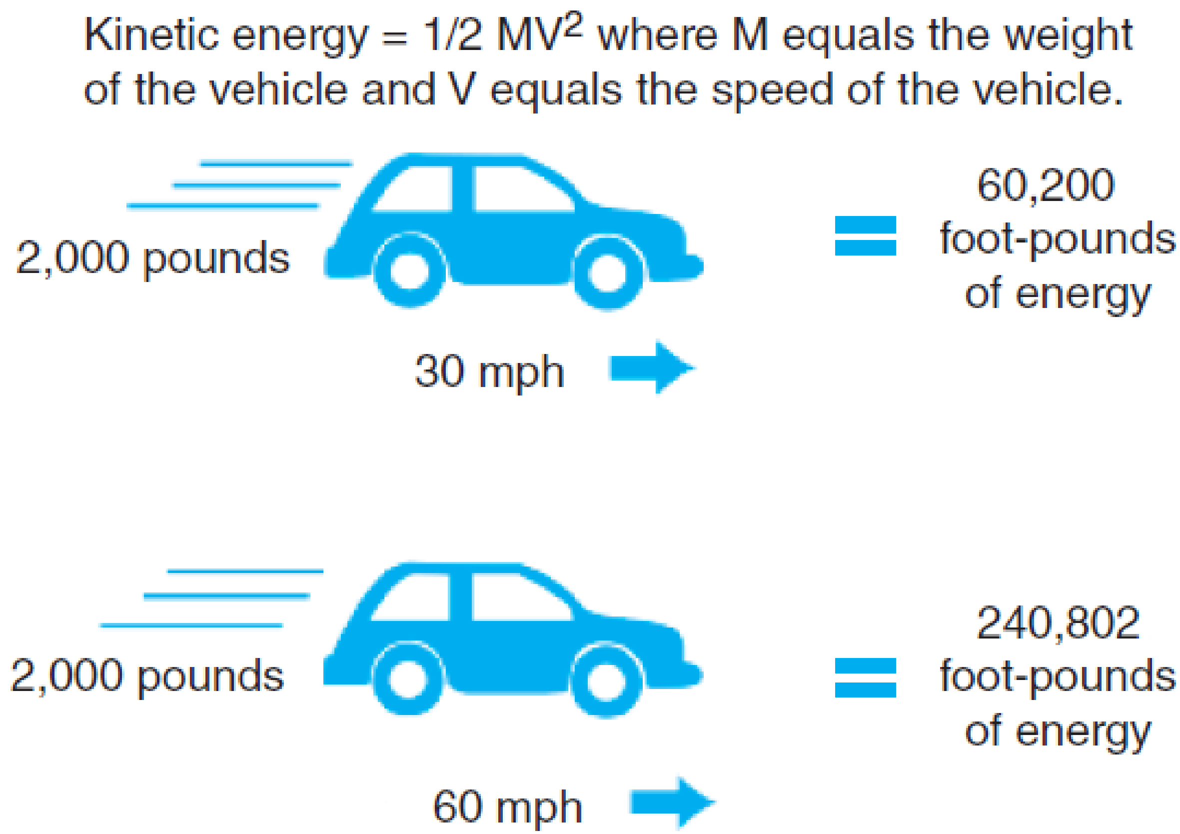
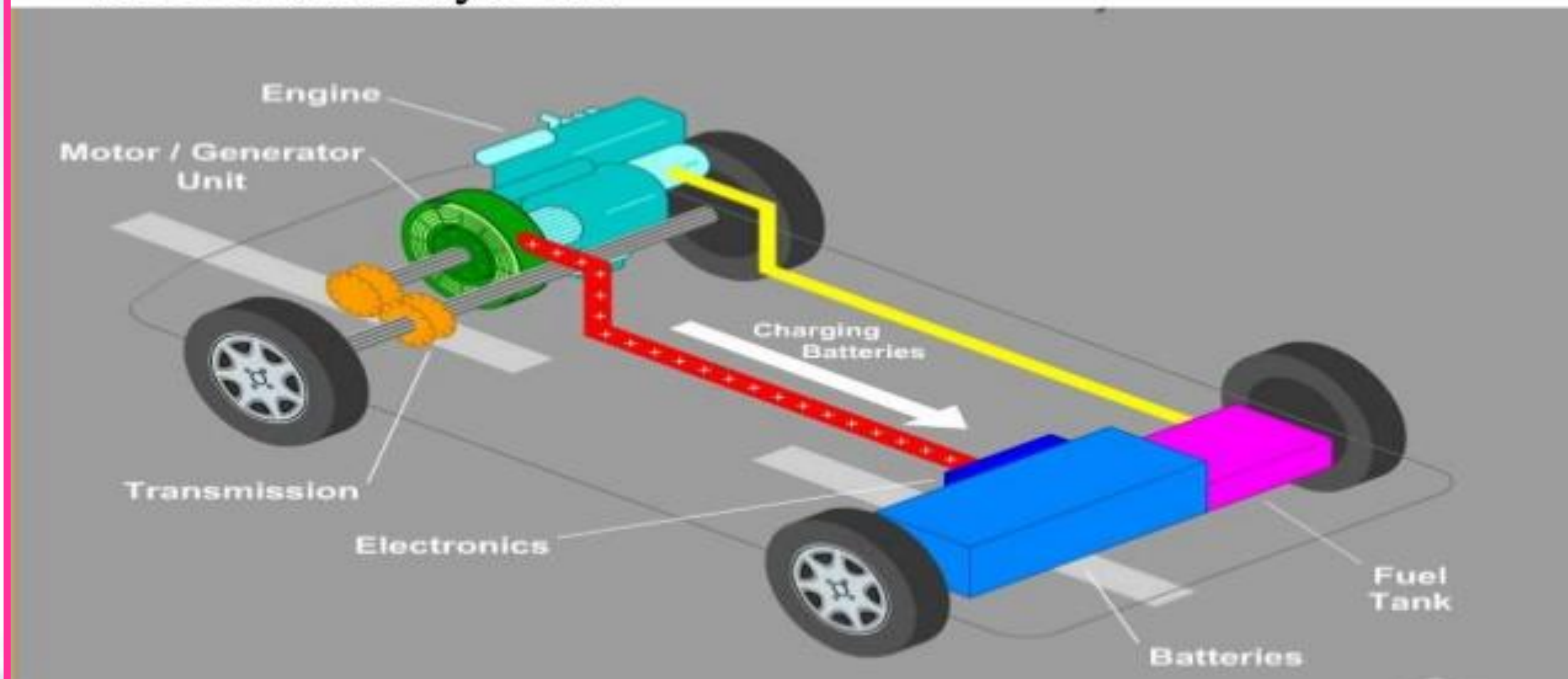


Figure 6-8 Kinetic energy increases exponentially with vehicle speed.

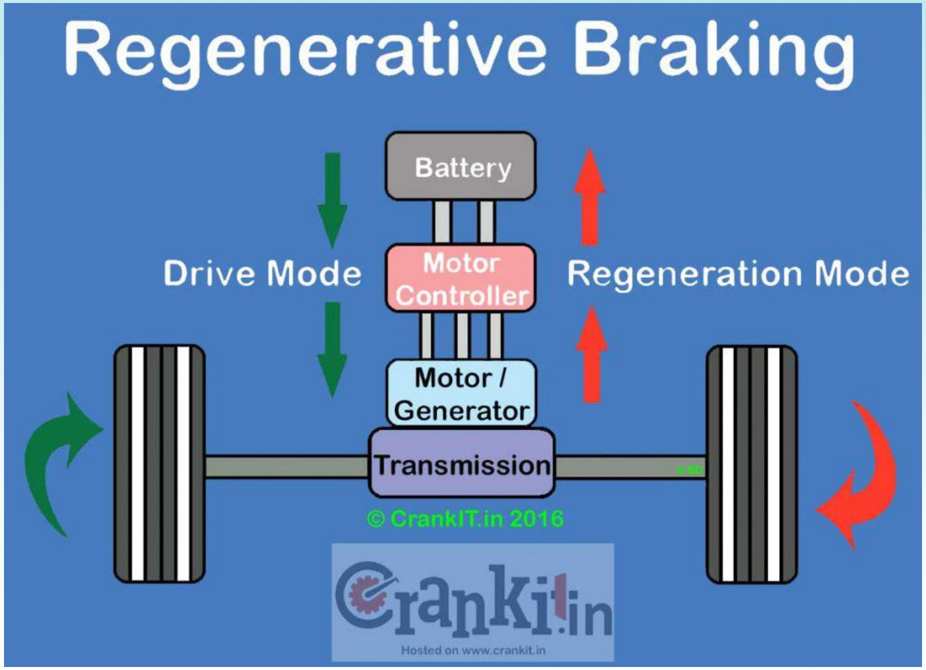
REGENERATIVE BRAKING

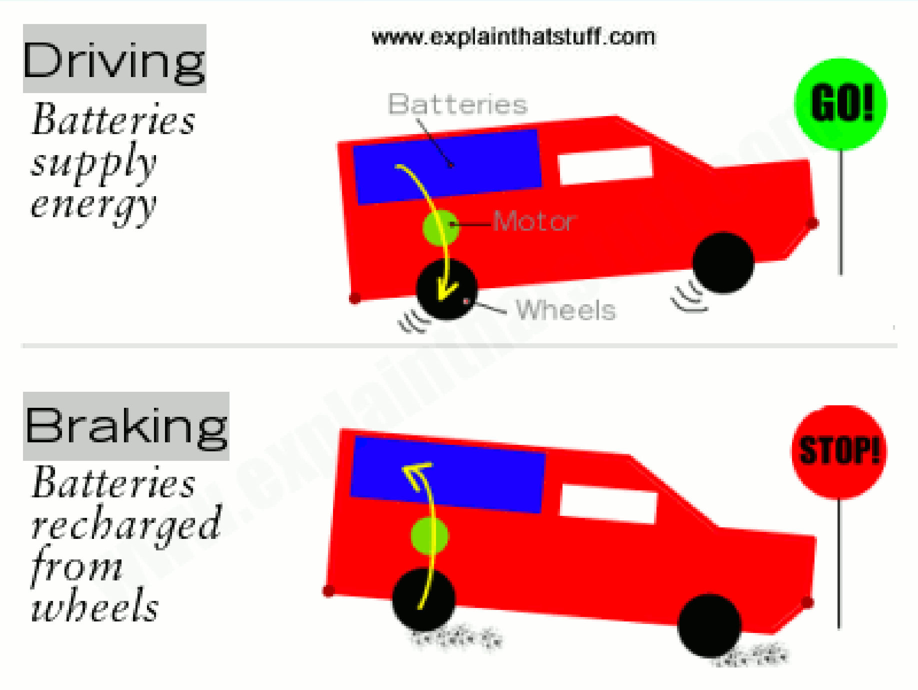
- During acceleration, the motor/generator unit acts as electric motor drawing electrical energy from batteries to provide extra driving force to move the vehicle.
- During braking electric supply from the battery is cut off by the electronic system.



Showing Charging of Battery when Brake Applied

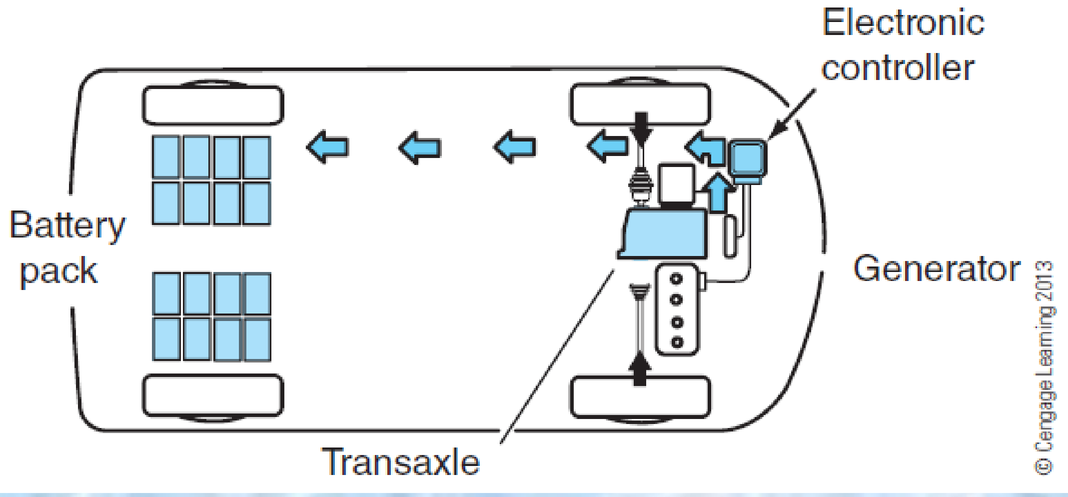
REGENERATIVE BRAKING





REGENERATIVE BRAKING

- Regenerative braking can capture approximately 30 % of energy normally lost during braking in conventional vehicles.
- It is claimed that electric energy resulting from regenerative braking supplies 20 % of energy used by Toyota Prius while driving in city traffic.
- In regenerative braking system, rotor of generator is turned by vehicle's wheels as vehicle is slowing down.
- Activation of the generator applies resistance to the drivetrain, causing wheels to slow down.
- K.E. of vehicle is changed to electrical energy until vehicle is stopped. At that point, there is no K.E.



REGENERATIVE BRAKING

- In many hybrids, there is no separate generator for braking system. Rather, the control system changes circuitry at motor and it acts as generator.
- Motor now converts motion into electricity rather than converting electricity into motion.
- Captured energy is sent to batteries or to an ultra-capacitor.
- Some hybrids use ultra-capacitors because they can capture energy quickly & can release it quickly during acceleration.
- Regenerative braking is not used to completely stop vehicle. Combination of hydraulic brakes & regenerative braking is used.

REGENERATIVE BRAKING

- Amount of energy captured by a regenerative braking system depends state of charge of battery, speed at which generator's rotor is spinning & how many wheels are part of regenerative braking system.

- Most current HEVs are front-wheel drive; therefore, energy can only be reclaimed at front wheels.

- Rear brakes still produce heat that is wasted.

PHEV

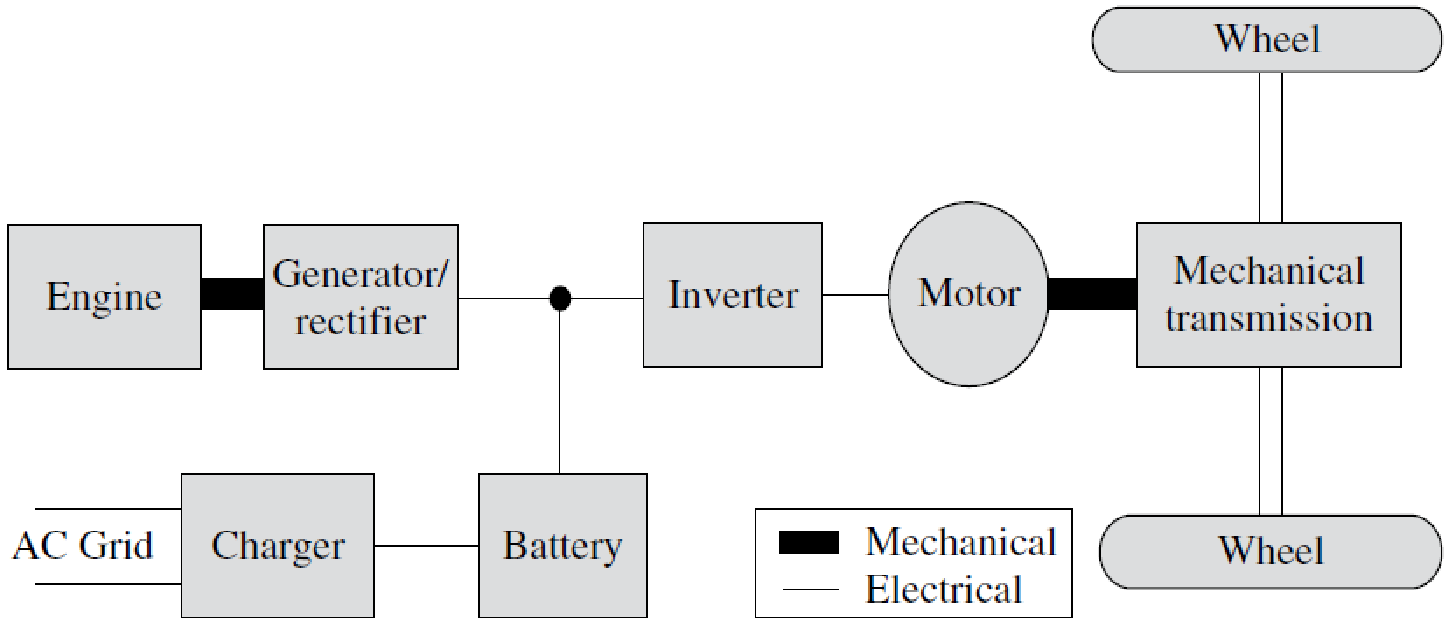


Figure 5.3 Series architecture of a PHEV.

- ICE is connected to a generator. Electricity generated by generator used to charge battery or supply power to motor.
- Electric motor is only component driving wheels.
- Motor can be induction motor/switched reluctance motor/permanent magnet motor.
- Motor can be mounted on vehicle in same way as in a conventional vehicle, without transmission.
- In-wheel hub motors can also be chosen.

PHEV

- **Parallel and complex hybrids can also be designed as PHEVs.**

- **In parallel & complex configurations, both engine & motor can drive the wheels. Hence, motor size can be smaller than those in series configurations.**

- **In comparison to HEVs, a parallel or complex PHEV will have a larger-sized battery pack, which provides a longer duration for extended electric drive.**

- **Engine is turned on whenever the vehicle’s power demand is high.**

Advantages of PHEV

- **Displacement of fossil fuel consumption in transportation sector.**
- **Reduction of emissions.**
- **Energy cost savings: Since electricity is cheaper than gasoline on an equivalent energy content, the cost per mile driven on electricity is cheaper than on gasoline.**
- **Maintenance cost savings: Since engine is not operating, or operating for much less time, there will be longer intervals for oil changes and other engine maintenance services.**
- **End-of-life use of battery: Batteries that can no longer provide desired performance in a PHEV can potentially be used for grid energy storage.**

ECONOMY OF PHEV

- Conventional vehicles is evaluated as fuel consumption (liter) per 100 km, or miles per gallon.
- Environmental Protection Agency, USA sets methods for fuel economy certification.
- One for city driving & One for highway driving.
- Combined fuel economy by combining 55% city and 45% highway MPG

$$FE_{MPG\_Combined} = \frac{1}{\frac{0.55}{FE_{city}} + \frac{0.45}{FE_{highway}}}$$

ECONOMY OF PHEV

- For pure EVs, fuel economy is described by electricity consumption for a certain range
- Ex: Wh/mile or kWh/100 km.
- Typical passenger car consumes 120–250 Wh/mile. In order to compare fuel efficiency of EVs with conventional car, the energy content of gasoline is used to convert the figures.
- Since 1 gallon of gasoline contains 33.7 kWh energy equivalent fuel economy of an EV can be expressed as

$$FE_{gas\_equivalent} = \frac{1}{\text{Wh/mile}} \times 33700$$

- A passenger car that consumes 240 Wh/mile will have an equivalent gasoline mileage of 140 MPG from energy point of view.

ECONOMY OF PHEV

Well-Wheel Efficiency:

$$FE_{EV\_well\_wheel} = \frac{1}{\text{Wh/mile}} \times 33700 \times \eta_{electricity}$$

$$FE_{ICEV\_well\_wheel} = FE_{mpg} \times \eta_{gasoline}$$

where $\eta_{electricity}$ = 30.3 and $\eta_{gasoline}$ = 83%

NOISE VIBRATION HARSHNESS

- HEV is subjected to frequent stopping and starting of engine to conserve fuel.

- Even too much stopping or starting of electric motor, leads to vibrations or stressing of engine, motor, or mechanical members associated with the system.

NOISE VIBRATION HARSHNESS

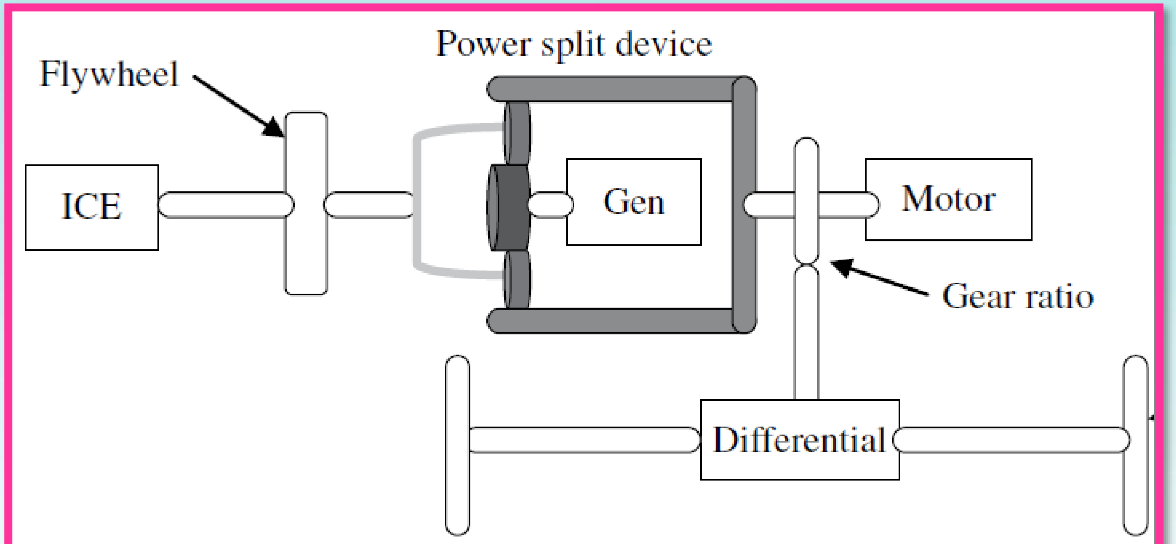


Figure 8.9 Configuration of a typical power split HEV.

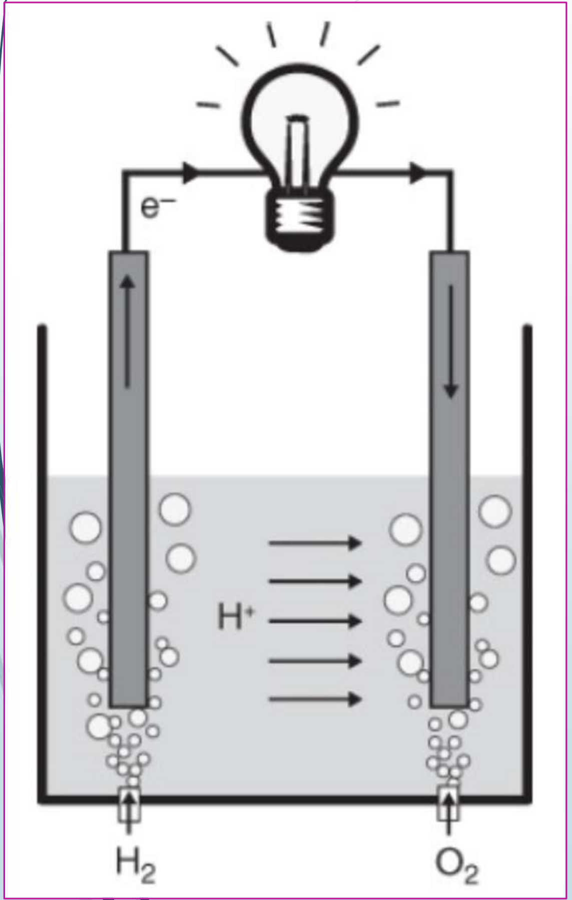
- **Planetary gear system is used to connect various items shown (typical for the Toyota HEV).**
- **Since there are no clutches, traction torque from ICE & electric motor is directly transmitted to wheels.**
- **Hence, if there is any engine start/stop action, accompanying vibration is transmitted to wheels through various members in between, including shafts & connecting gears.**

NOISE VIBRATION HARSHNESS

- Vibration from engine can occur both before and after ignition.
- When there is no ignition, there is compression and pumping pressure in the cylinders.
- After ignition, there will be a sudden torque change in engine due to combustion.
- Vibration was reduced by using two controllers, first one controlling ripple due to compression and pumping pressures in the engine cylinder & second controlling torsional vibration caused by rapid changes in the torque.

FUEL CELL FOR ELECTRIC VEHICLES

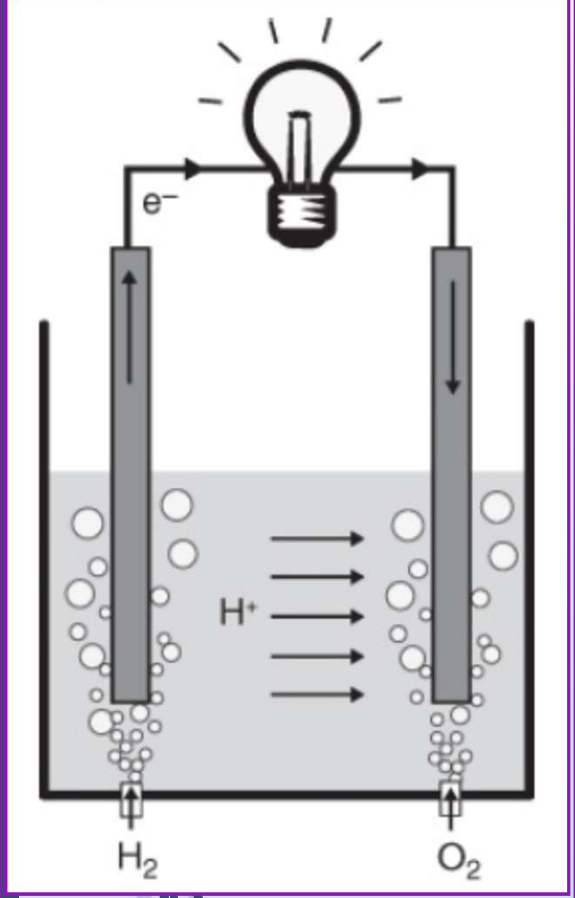
FUEL CELL



FUEL CELL	BATTERY
✓ In a fuel cell, chemicals constantly flow into the cell so it never goes dead.	✓ A battery has all of its chemicals stored inside, and it converts those chemicals into electricity too. This means that a battery eventually "goes dead.
✓ As long as there is a flow of chemicals into the cell, the electricity flows out of the cell.	✓ But in case of battery it eventually "goes dead" we either throw it away or recharge it

Fuel cell is an electrochemical device that produces electricity without combustion by combining hydrogen and oxygen to produce water/heat.

FUEL CELL: PRINCIPLE

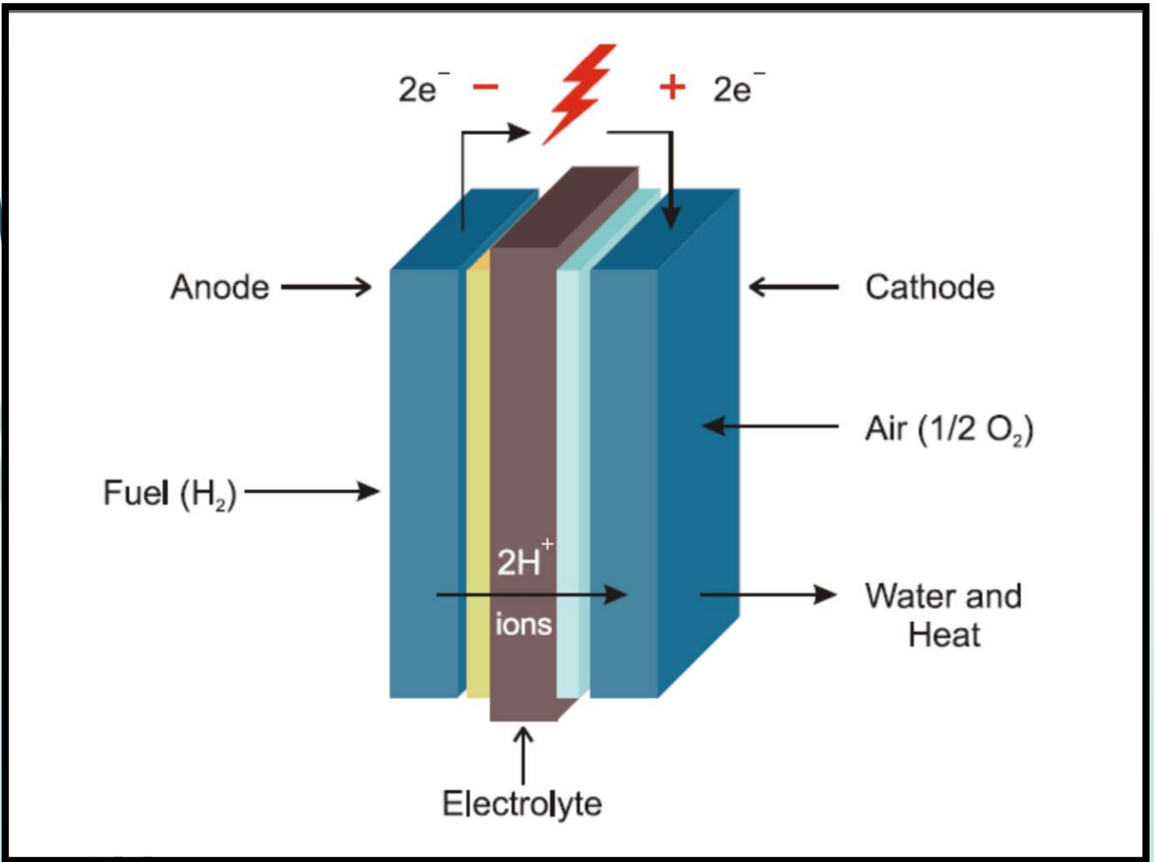


- Consists of two Pt electrodes dipped into sulfuric acid (an aqueous acid electrolyte).
- H_2 gas, bubbled across left electrode, is split into protons (H^+) and e^-.

$$H_2 \longrightarrow 2H^+ + e^-$$

$$\tfrac{1}{2} O_2 + 2H^+ + e^- \longrightarrow H_2O$$

- Protons flow through electrolyte, but e^- cannot.
- Instead, e^- flow from left to right through a piece of wire that connects Pt electrodes.
- When e^- reach right electrode, they recombine with H^+ and bubbling O_2 gas to produce H_2O.
- If a load (e.g., a light bulb) is introduced flowing e- will provide power to load, causing light bulb to glow.



- Amount of power produced depends upon fuel cell type, cell size, operating temperature or pressure.

- Single fuel cell produces electricity for only small applications.

- Individual fuel cells are typically combined in series into a fuel cell stack. Which consists of hundreds of fuel cells.

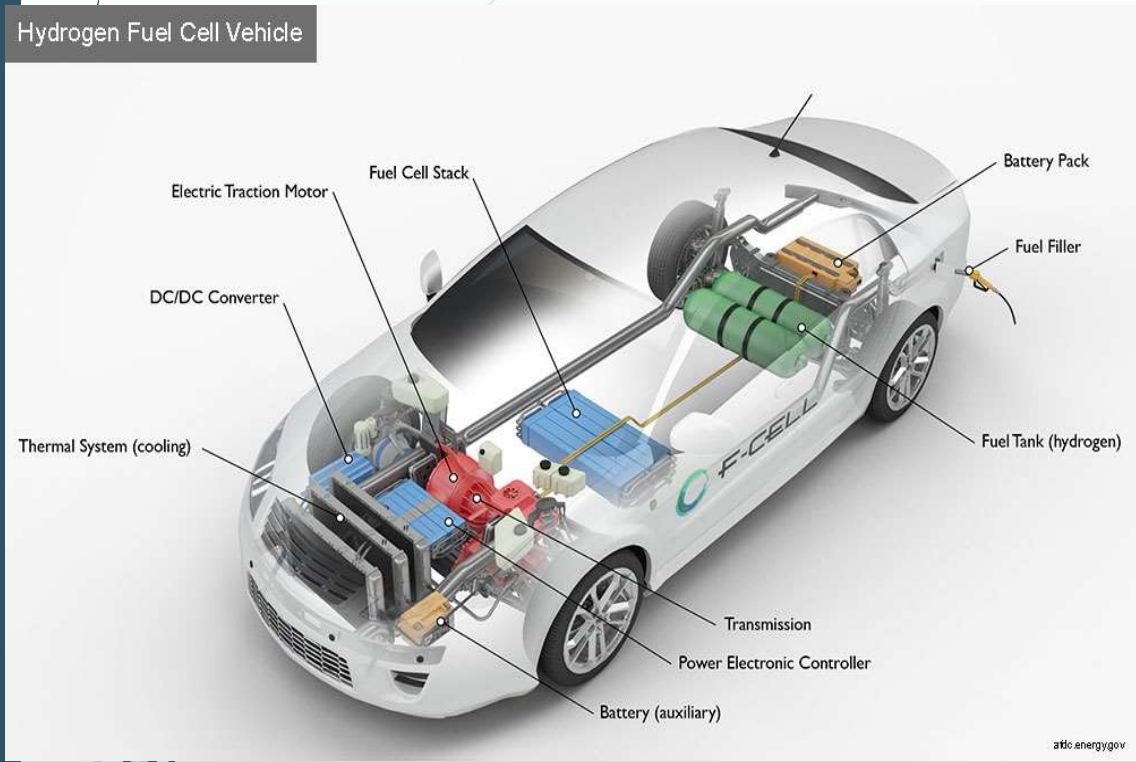
ADVANTAGES

- **Zero Emissions:** a fuel cell vehicle only emits water vapour. Therefore, no air pollution occurs.
- **High efficiency:** Fuel cells convert chemical energy directly into electricity without the combustion process. As a result, Fuel cells can achieve high efficiencies in energy conversion.
- **High power density:** A high power density allows fuel cells to be relatively compact source of electric power, beneficial in application with space constraints.
- **Quiet operation:** Fuel cells can be used in residential or built-up areas where the noise pollution can be avoided.
- **No recharge:** Fuel cell systems do not require recharging

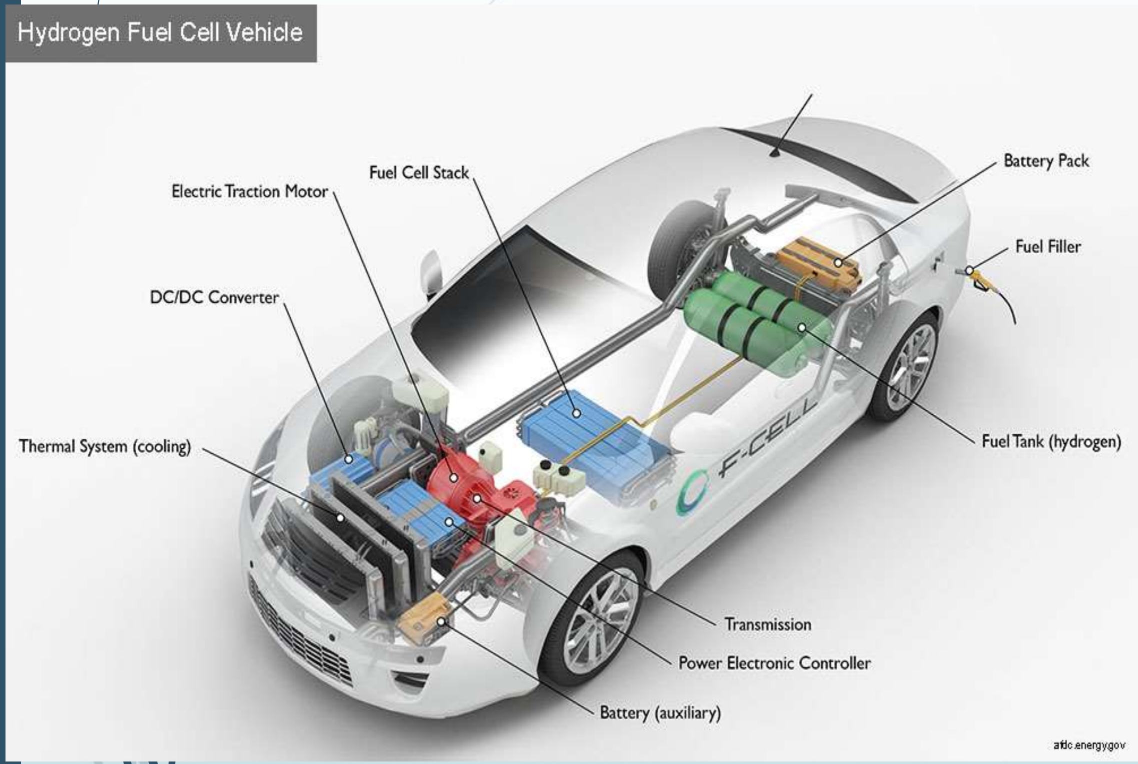
Disadvantages of Fuel Cells

- High initial cost.
- Life times of the cells are not accurately known.
- Large weight and volume of gas fuel storage system.
- High cost of pure hydrogen.
- Hydrogen can be stored in lesser volume by liquefaction but liquefaction itself require 30% of the stored energy.
- Lack of infrastructure for distributing hydrogen.

COMPONENTS OF FUEL CELL (OR) H_2 VEHICLE



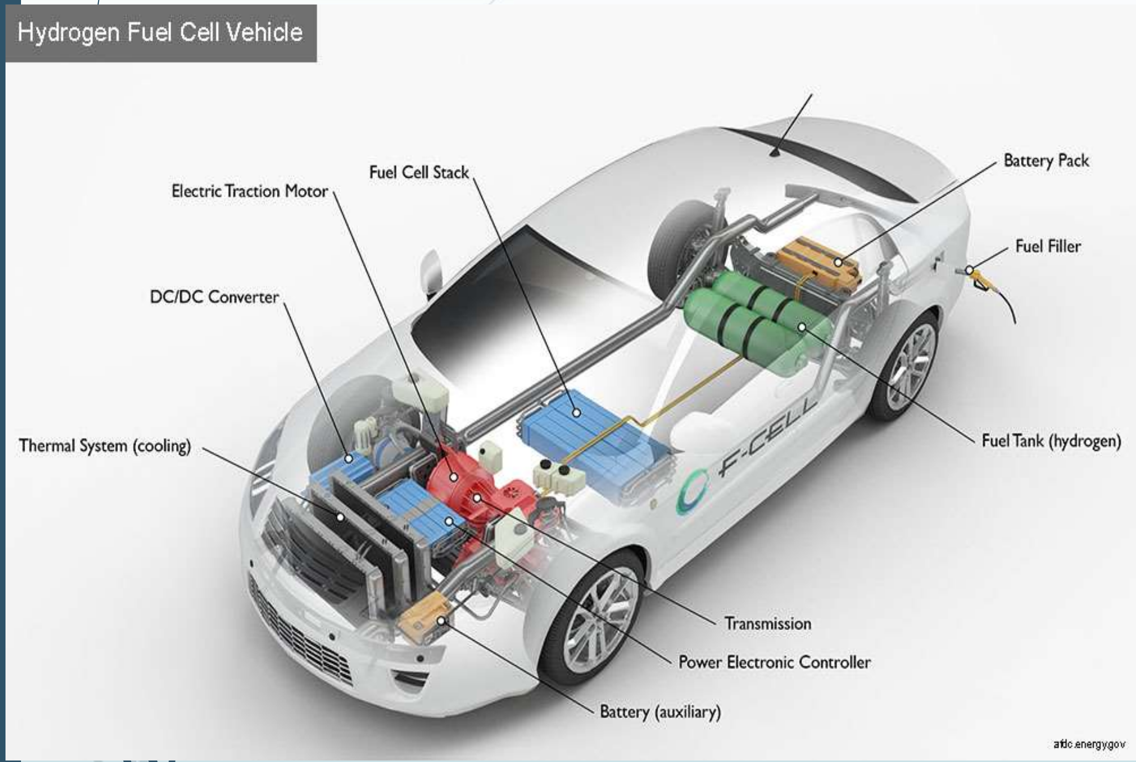
- H_2 - fuel
- H_2 is stored in tanks in the vehicle or can be provided by a reformer that extracts H_2 from gasoline, methanol, or natural gas.
- Major obstacle is absence of infrastructure for supplying pure hydrogen.
- Reformer answers that concern, as required fuels are readily available.
- However, cost of the reformer adds to high cost of a fuel cell.



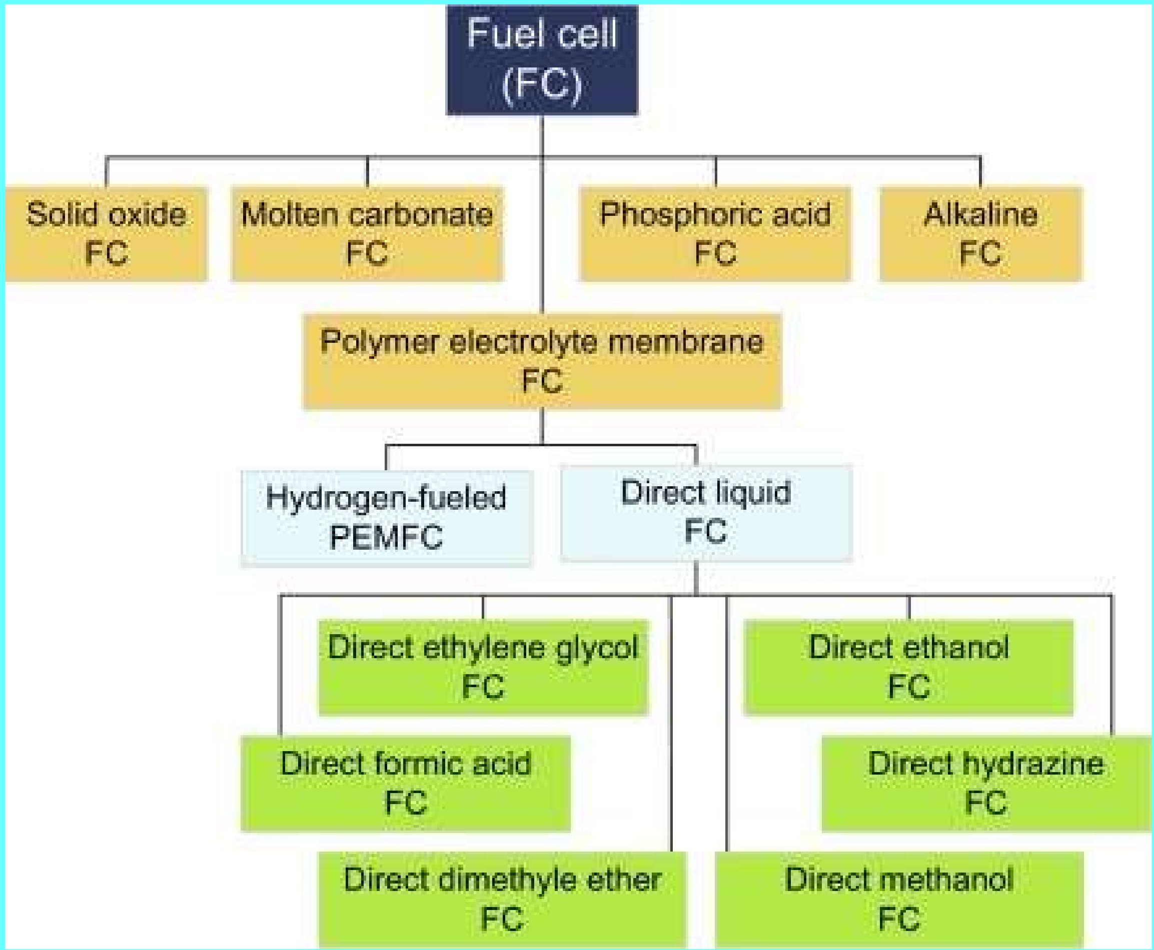
- Ford & Daimler are owners of Ballard Power Systems Inc., leading developer and manufacturer of fuel cell stacks. Supplied fuel cells to Mitsubishi, Nissan, Volkswagen, and Honda.

- Fuel cell vehicle is much like a battery-operated electric vehicle. Electricity powers an electric motor to drive the vehicle.

- Vehicle operates very quietly & output of CO_2/harmful emissions is zero, unless it relies on fuel reformer.

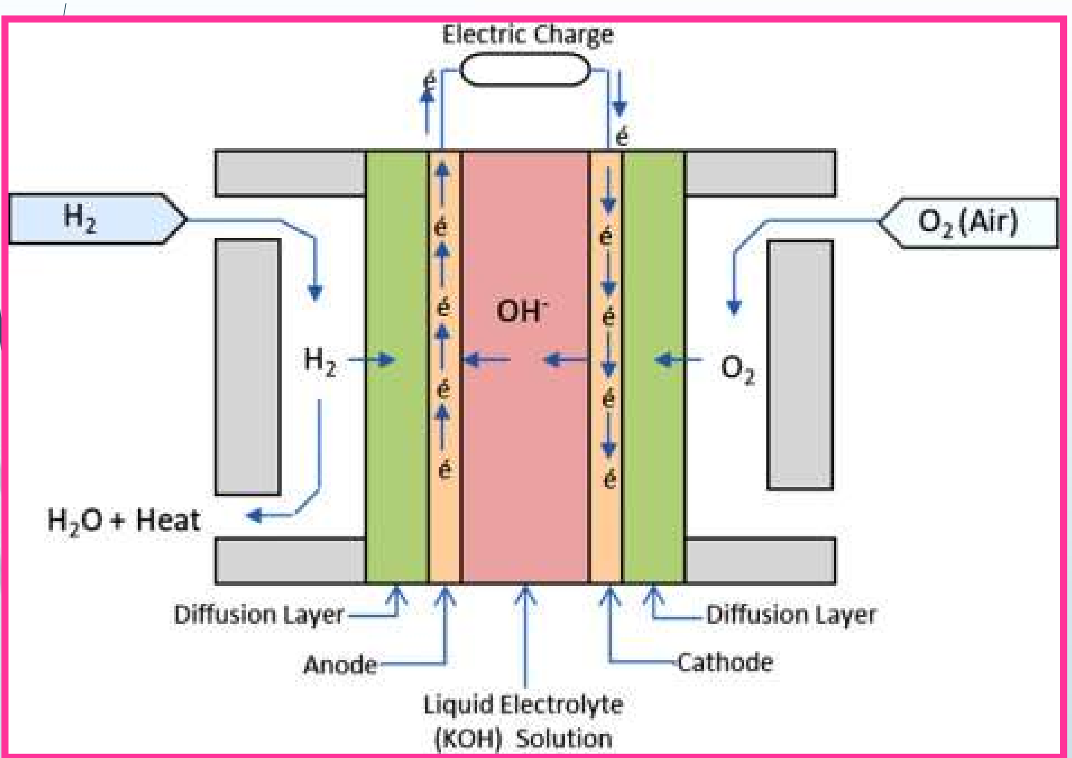


- **Fuel cell stack—An electrical generation device made up of several individual fuel cells.**
- **High-pressure hydrogen supply system or reformer with a fuel tank.**
- **Air supply system— Pump to supply fuel cells with air.**
- **Humidification system—Recycles water vapor generated in FC stack to humidify H_2 & air, so fuel cell's membrane does not dry out.**
- **Fuel cell cooling system.**
- **Storage battery or ultra-capacitor.**
- **Traction motor and transmission.**
- **Control module includes DC/DC converter.**



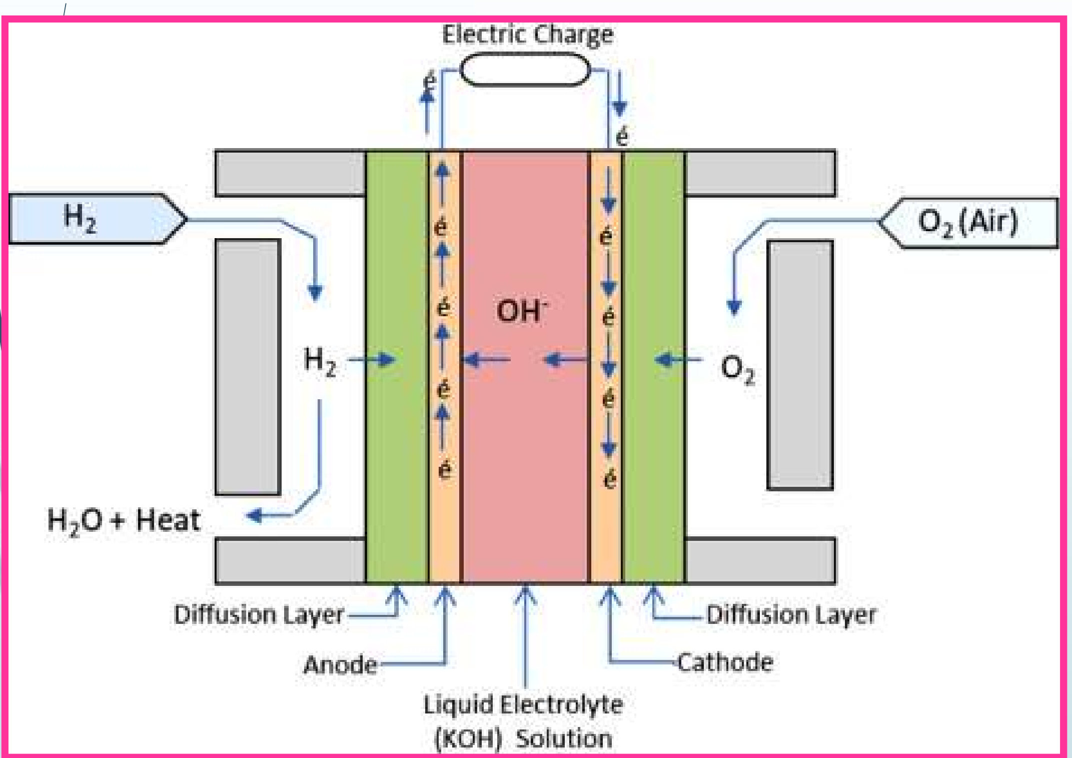
- **Alkaline Fuel cell (AFC)**
- **Phosphoric Acid Fuel cell (PAFC)**
- **Polymer Electrolytic Membrane Fuel Cell (PEMFC)**
- **Molten Carbonate Fuel Cell (MCFC)**
- **Solid Oxide Fuel Cell (SOFC)**

ALKALINE FUEL CELL (AFC)

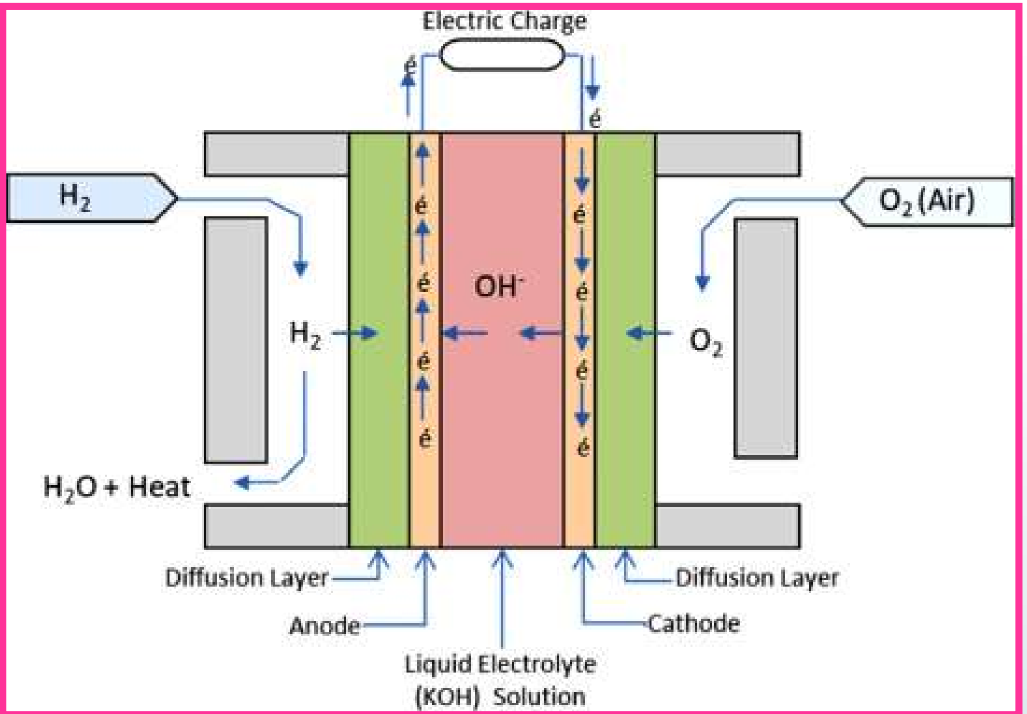


- Electrolyte composed of molten alkaline mixture (KOH).
- Electrolyte that conducts oxide (OH^-) ions from cathode to anode.
- Alkaline fuel cells operate at about 65-220ºC & pressure of 1 bar.
- Each cell produce 1.1-1.2 V DC.
- Electrolyte can be mobile or immobile.

ALKALINE FUEL CELLS (AFC)



- **Mobile alkaline electrolyte fuel cells use fluid electrolyte that continuously circulates between electrodes.**
- **Immobile alkaline electrolyte fuel cells use an electrolyte that consists of a thick paste retained by capillary forces within a porous support matrix such as asbestos.**
- **Product water evaporates into the source hydrogen gas stream at anode from which it is subsequently condensed.**
- **Waste heat is removed by way of a circulating coolant.**



Reaction

Alkaline fuel cells must operate using pure hydrogen free of carbon oxides.

The reactions at the anode are:

(1) $H_2 + 2K^+ + 2OH^- \Rightarrow 2K + 2H_2O$

(2) $2K \Rightarrow 2K^+ + 2e^-$

The reactions at the cathode are:

(1) $\frac{1}{2}O_2 + H_2O \Rightarrow 2OH$

(2) $2OH + 2e^- \Rightarrow 2OH^-$

- **OH^- ion is drawn through electrolyte from cathode to anode by the reactive attraction of H_2 to O_2, while e^- are forced through an external circuit from anode to cathode.**

Combining the anode and cathode reactions, the overall cell reactions are:

(1) $H_2 + 2OH^- \Rightarrow 2H_2O + 2e^-$

(2) $\frac{1}{2}O_2 + H_2O + 2e^- \Rightarrow 2OH^-$

Advantages & Disadvantages of AFC

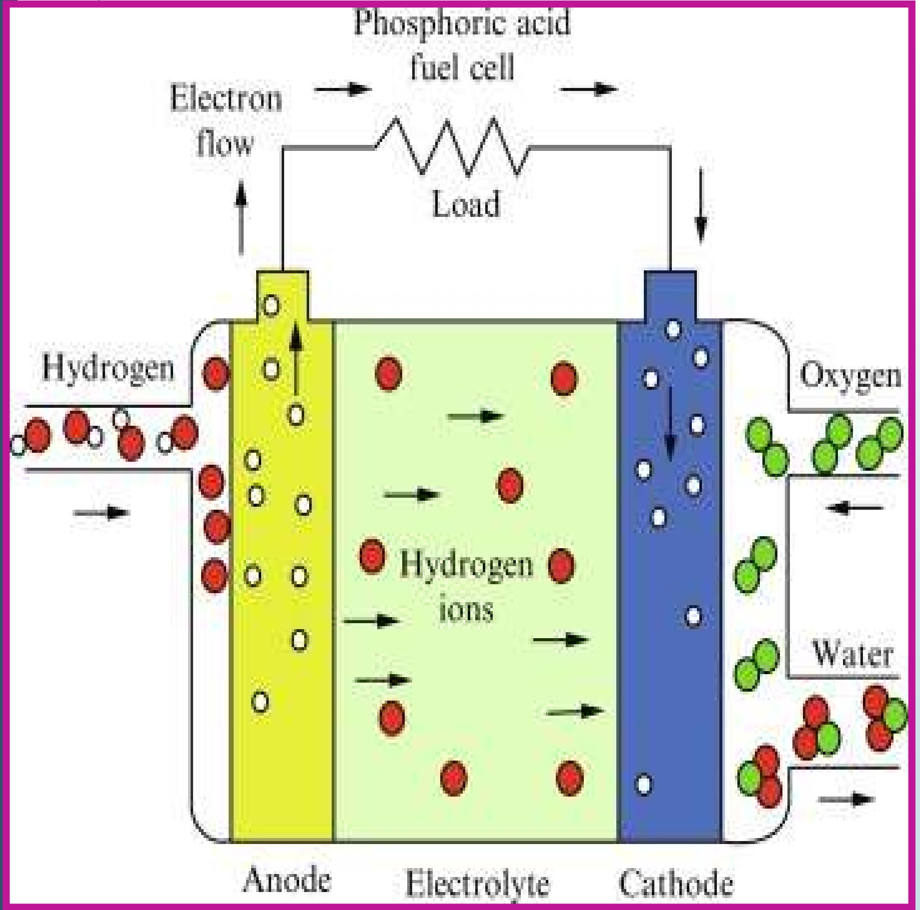
ADVANTAGES

- Operates @ low temperature.
- Low weight & volume.
- Fast start up time & High efficiency
- Have minimum corrosion & ease of operation.
- Do not need expensive metal catalysts

DISADVANTAGES

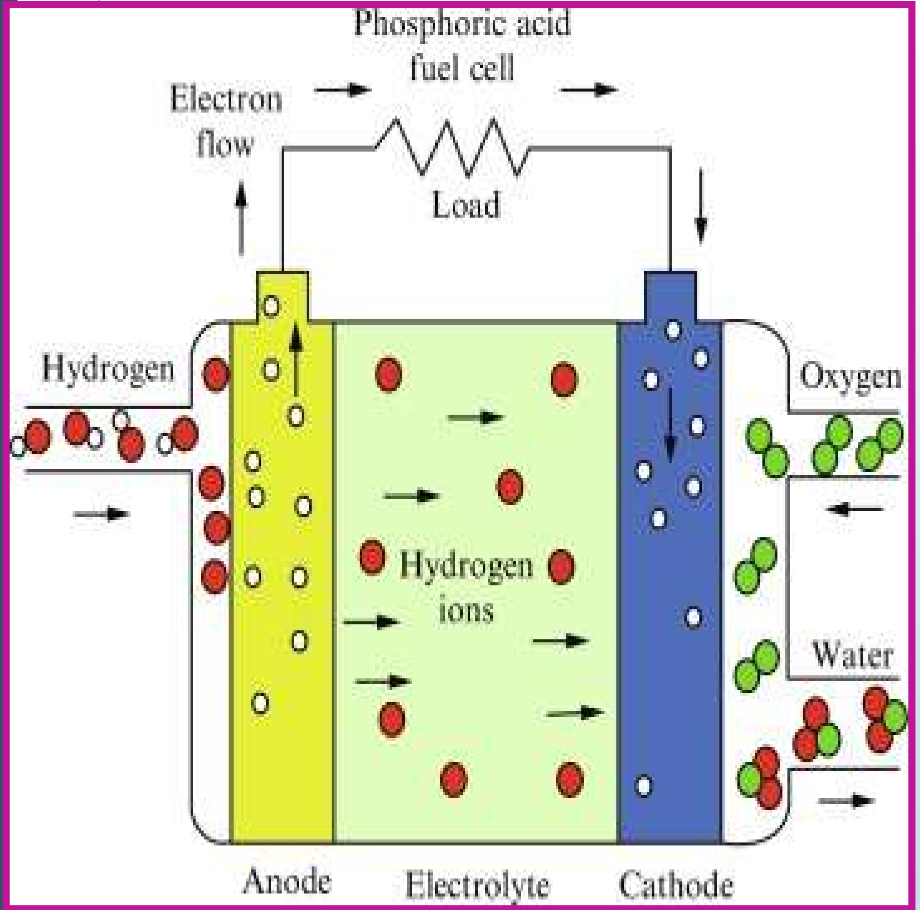
- Oxidant must be either pure oxygen or air that has been scrubbed free of CO_2. Fuel must be pure H_2 due to presence of CO_2 in reformate as it is extremely intolerant to CO_2.
- Require liquid handling management system as it uses liquid electrolyte..
- Have short life time.
- Requires complex water management.

PHOSPHORIC ACID FUEL CELL (PAFC)



- Electrolyte is composed of liquid phosphoric acid within a SiC matrix material.
- PAFCs use an electrolyte that conducts hydrogen ions (H+) from anode to cathode.
- PAFC operate at about 150-250ºC and a pressure of 15 bar.
- Each cell can produce up to 1.1 V DC.

PHOSPHORIC ACID FUEL CELL (PAFC)



- **Reaction at anode:**

  $$H_2 \longrightarrow 2H^+ + 2e^-$$

- **Reaction at cathode:**

  $$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O$$

- **H^+ ion is drawn through electrolyte from anode to cathode by reactive attraction of H_2 to O_2, while e^- are forced through an external circuit.**

Advantages & Disadvantages of PAFC

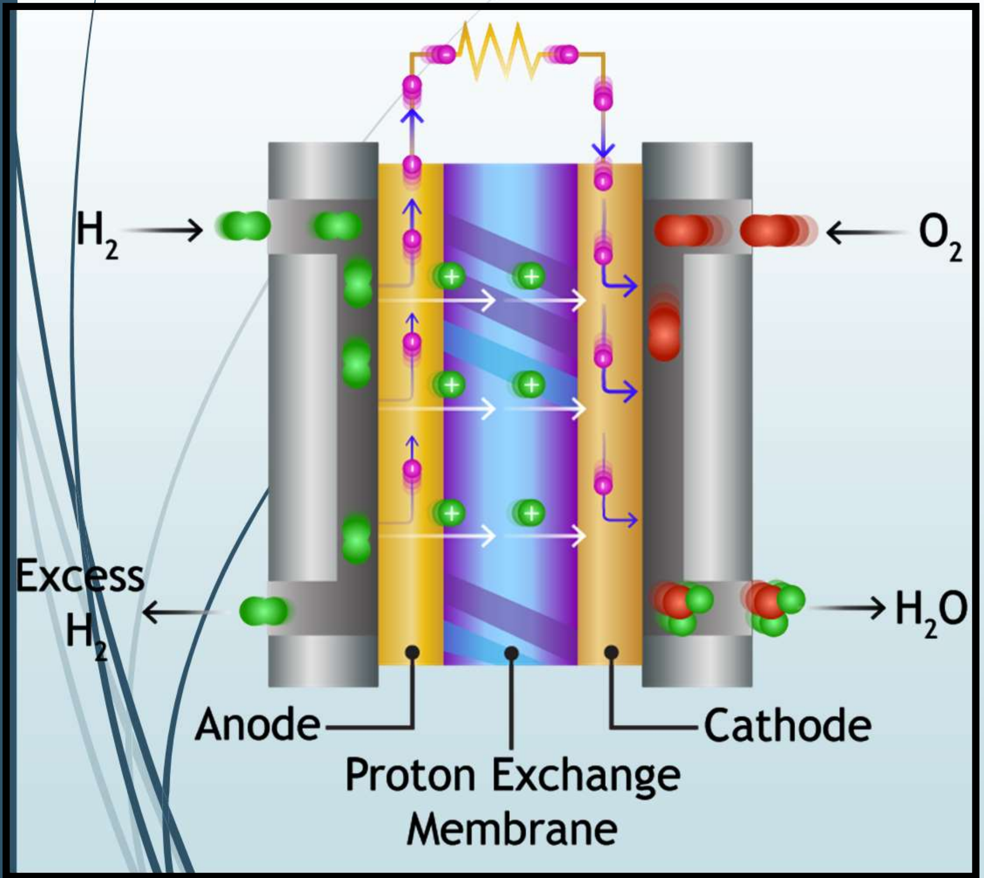
ADVANTAGES

- Are tolerant of CO_2 (up to 30%). Hence, phosphoric acid fuel cells can use unscrubbed air as oxidant.
- Operate at low temperature, Thus, they produce higher grade waste heat that can potentially be used in co-generation applications.
- Stable electrolyte characteristics with low volatility even at operating temp. as high as 200˚C.

DISADVANTAGES

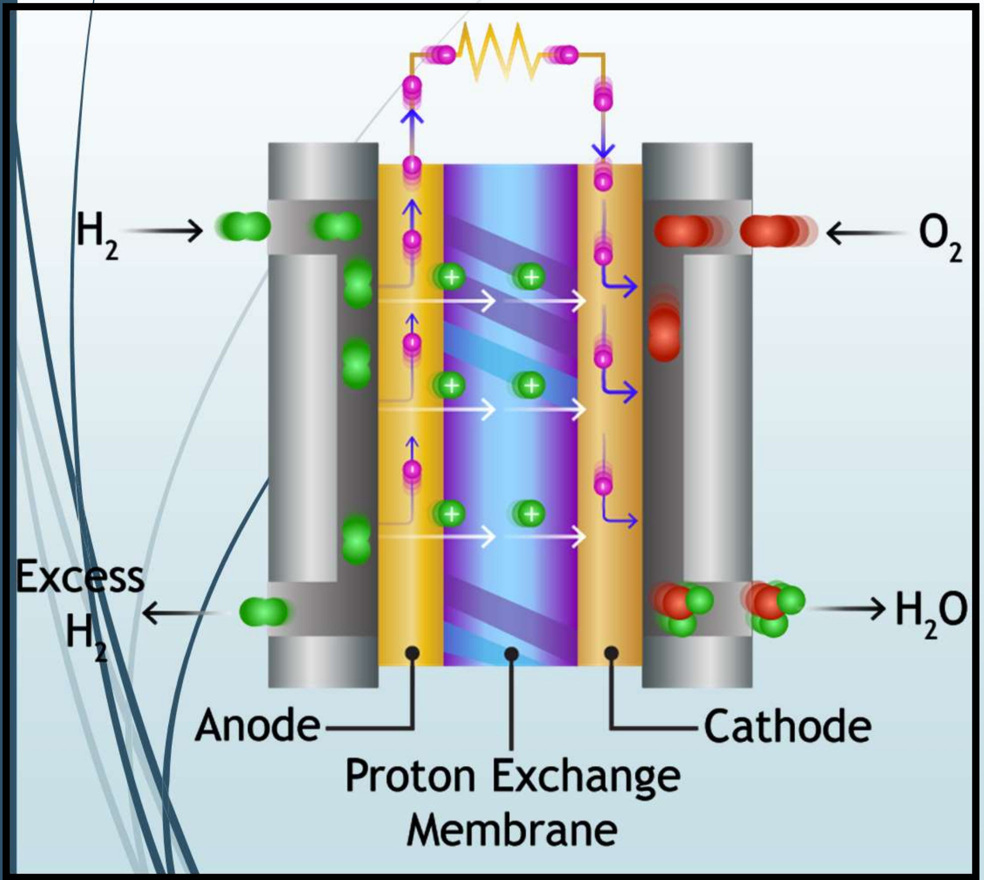
- Tolerate only about 2% CO & 50 ppm of total sulfur compounds.
- Use a corrosive liquid electrolyte resulting in material corrosion problems.
- Liquid electrolyte, introducing liquid handling problems. Electrolyte slowly evaporates over time.
- Allow product water to enter and dilute the electrolyte.
- Large and heavy & have to be warmed up before they are operated.

POLYMER ELECTROLYTE MEMBRANE FUEL CELL (PEMFC)



- Also known as Proton exchange membrane fuel cell.
- Best candidate for cars.
- Electrolyte is composed of a solid polymer film that consists of a form of acidified Teflon.
- PEMFC operate at relatively low temperature around 80ºC & 1-2 bar.
- Each cell can produce up to 1.1 V DC.

POLYMER ELECTROLYTE MEMBRANE FUEL CELL (PEMFC)



- **Reactions at anode:**

$$H_2 \longrightarrow 2H^+ + 2e^-$$

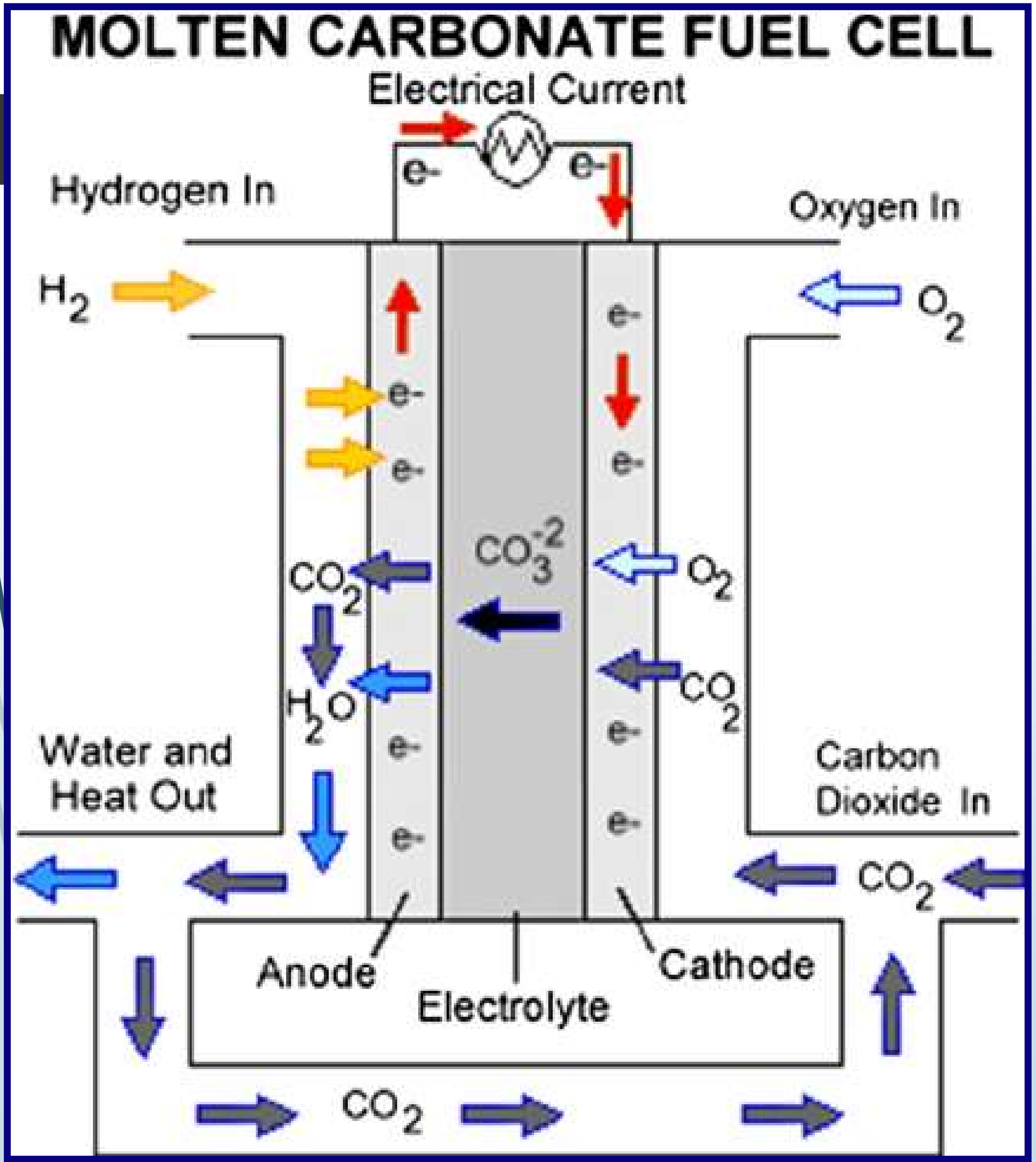
- **Reaction at cathode:**

$$\tfrac{1}{2}O_2 + 2H^+ + 2e^- \longrightarrow H_2O$$

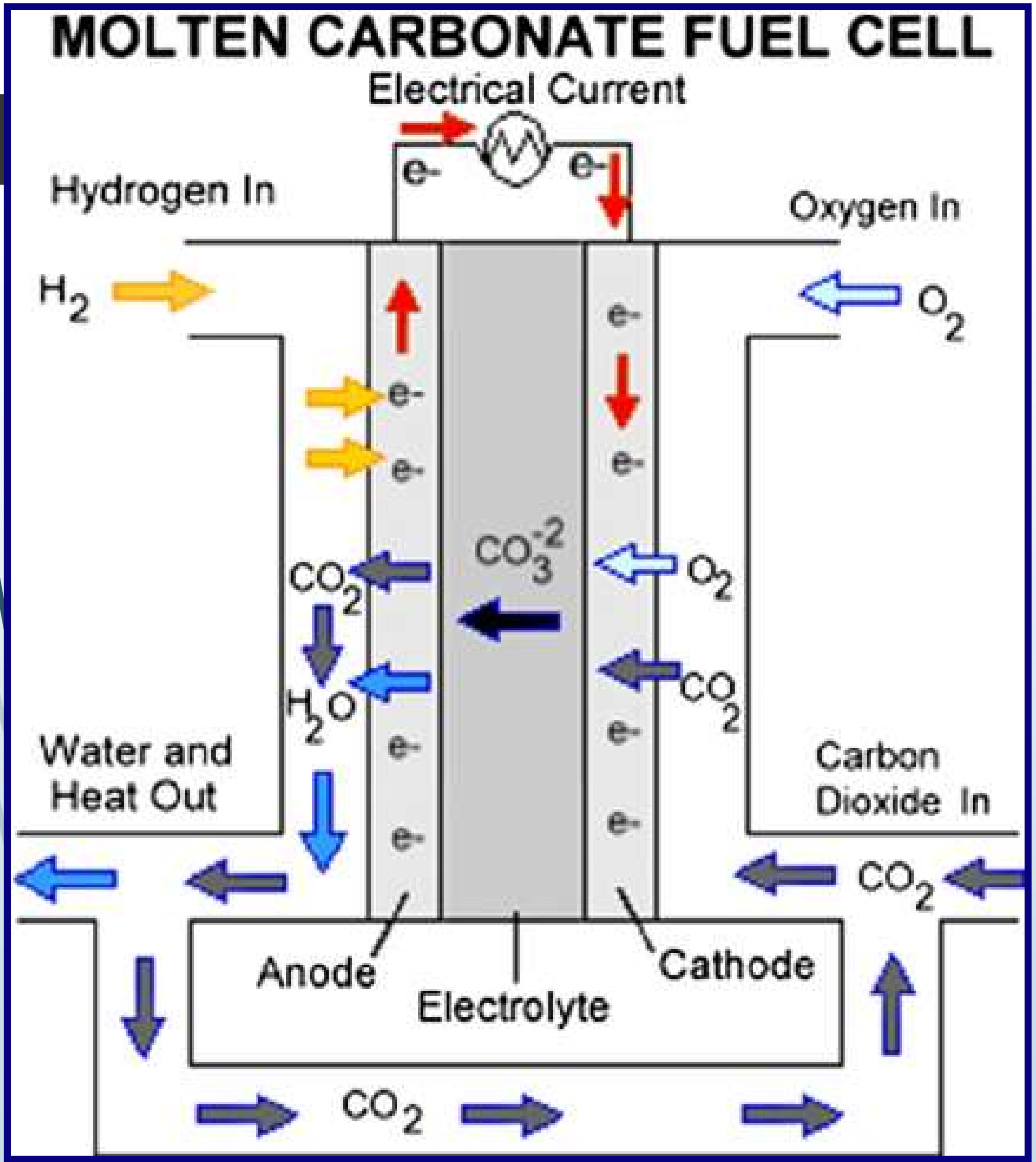
- **H^+ ion is drawn through electrolyte from anode to cathode by reactive attraction of H_2 to O_2, while e- are forced through an external circuit.**

Advantages & Disadvantages of PEMFC

ADVANTAGES	DISADVANTAGES
Tolerant of carbon dioxide. As a result & can use unscrubbed air as oxidant.	Can tolerate only about 50 ppm CO & few ppm of sulfur compounds.
Operate at low temperatures. This simplifies materials issues, provides for quick startup and increases safety.	Need reactant gas humidification.
Use a solid, dry electrolyte eliminates liquid handling problems.	Humidification is energy intensive and increases the complexity of the system.
Use a non-corrosive electrolyte. Pure water operation minimizes corrosion problems and improves safety.	Use an expensive Pt catalyst.
Have high voltage, current and power density.	Use an expensive membrane that is difficult to work with.
Compact and rugged & simple mechanical design.	



- **Electrolyte is of molten mixture of lithium & potassium carbonates.**
- **Molten carbonate fuel cells use an electrolyte that conducts carbonate (CO_3^{2-}) ions from cathode to anode.**
- **Molten carbonate fuel cells operate at about 650ºC and a pressure of 1-10 bar.**
- **Each cell can produce up to 0.7-1.0 V DC.**



- Molten carbonate fuel cells can operate using pure H_2 or hydrocarbon fuels.
- When a hydrocarbon (methane), is introduced to anode in the presence of water, it absorbs heat and undergoes a steam reforming reaction:

$$CH_4 + H_2O \longrightarrow 3H_2 + CO$$

- Reactions at anode:

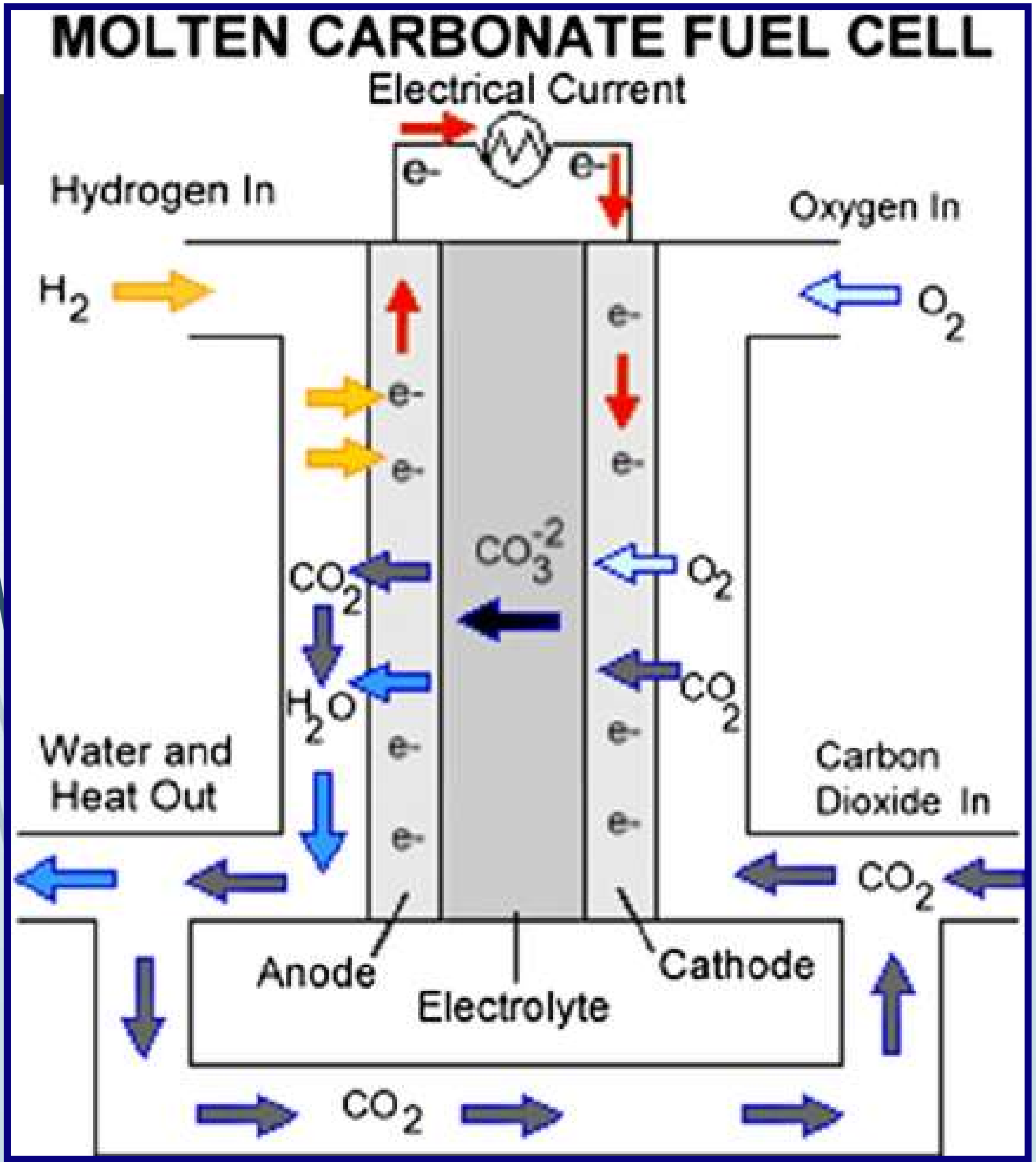
$$3H_2 + 3CO_3^{2-} \longrightarrow 3H_2O + 3CO_2 + 6e^-$$

$$CO + CO_3^{2-} \longrightarrow 2CO_2 + 2e^-$$

- Reaction at cathode:

$$2O_2 + 4CO_2 + 8e^- \longrightarrow 4CO_3^{2-}$$

- CO_3^{2-} ion is drawn through electrolyte from cathode to anode by the attraction of H_2 & CO to O_2, while e- forced through an external circuit from anode to cathode.



- **Combining anode and cathode reactions, overall reactions are:**

$$2H_2 + O_2 \longrightarrow 2H_2O$$

$$CO + \frac{1}{2}O_2 \longrightarrow CO_2$$

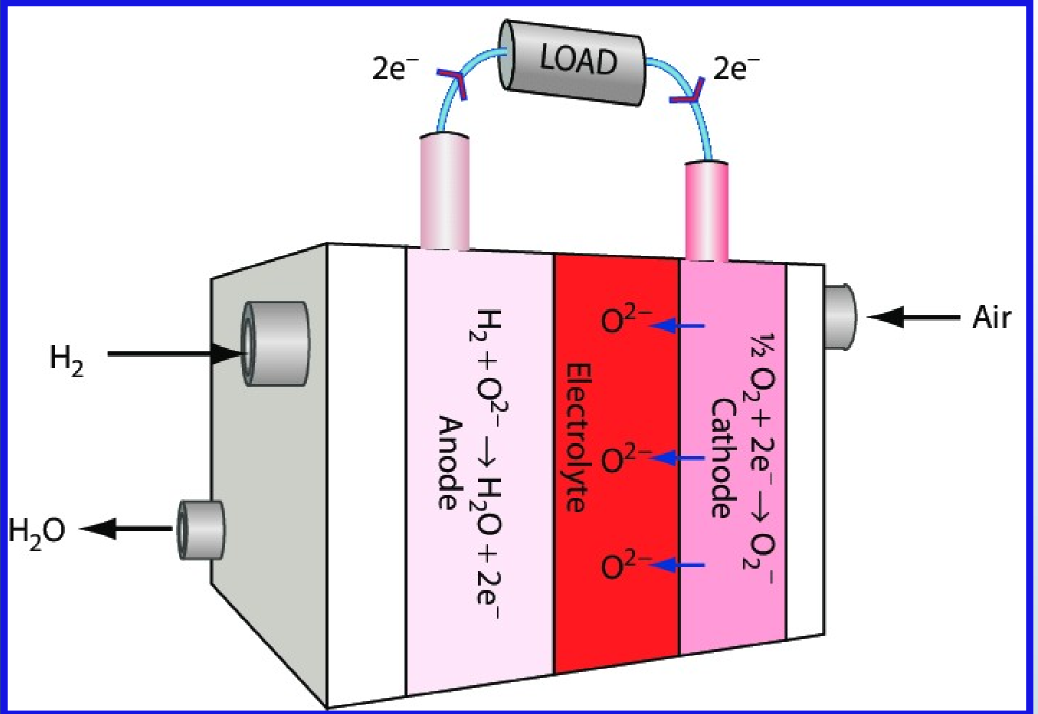
- **Fuel cell produces water, regardless of fuel, and CO_2 if using a hydrocarbon fuel.**

- **Both water & CO_2 must be continually removed from cathode to facilitate further reaction.**

Advantages & Disadvantages of MCFC

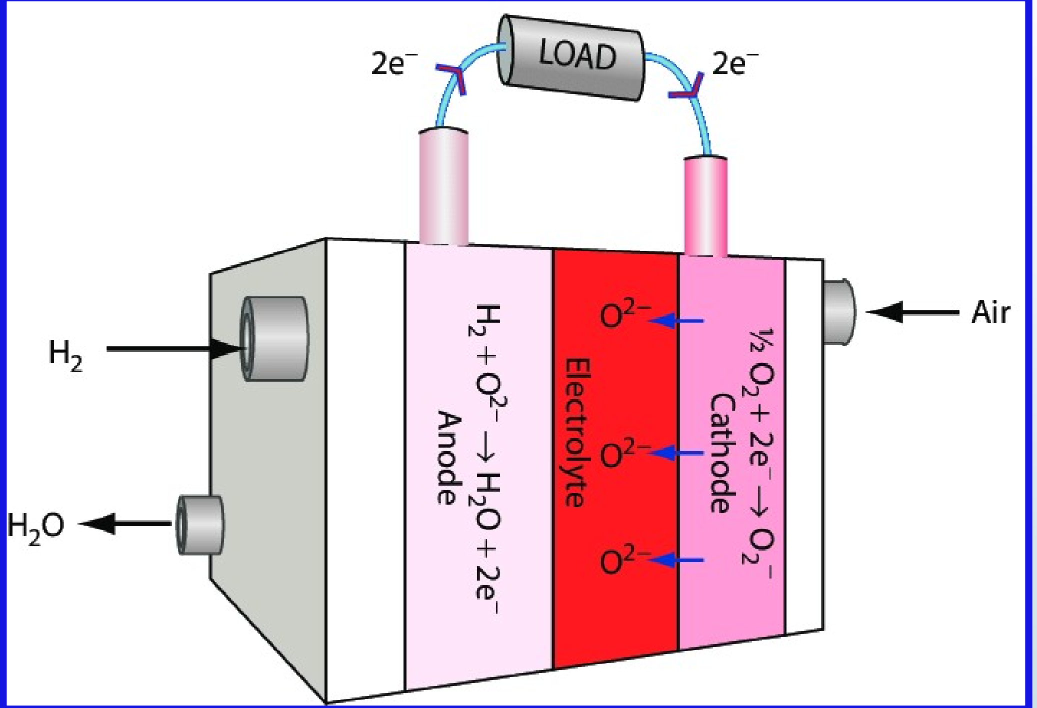
ADVANTAGES	DISADVANTAGES
Support spontaneous internal reforming of light hydro-carbon fuels	Corrosion is a problem and cause loss of electrolyte, deterioration of separator plates.
Generate high-grade waste heat	Require suitable materials that are resistant to corrosion, are dimensionally stable.
Fast reaction kinetics	Have a high intolerance to sulfur to sulfur compounds suffering a significant performance loss.
High efficiency	Have a liquid electrolyte, which introduces liquid handling problems.
Do not need noble metal catalysts	Require a considerable warmup period.

Solid Oxide Fuel Cell



- Electrolyte composed of solid oxide, usually zirconia (stabilized with rare earth element oxides like yttrium), takes the form of ceramic.
- Electrolyte that conducts oxide (O^{2-}) ions from cathode to anode .
- Solid oxide fuel cells operate at about 1830 ºF (1000 ºC) and a pressure of 15 psig (1 barg).
- Each cell produce between 0.8 - 1.0 V DC.

Solid Oxide Fuel Cell



- Combining anode & cathode reactions, overall reactions are:

$$2H_2 + O_2 \longrightarrow 2H_2O$$

$$CO + \frac{1}{2}O_2 \longrightarrow CO_2$$

- Fuel cell produces water, regardless of fuel, and CO_2 if using a hydrocarbon fuel.

- Both water & CO_2 must be continually removed from cathode to facilitate further reaction.

Advantages & Disadvantages of SOFC

ADVANTAGES

- Support spontaneous internal reforming of light hydro-carbon fuels
- Generate high-grade waste heat
- Fast reaction kinetics & High efficiency
- Have a solid electrolyte, avoiding problems associated with handling liquids.
- Do not need noble metal catalysts

DISADVANTAGES

- Technology is not yet mature.
- Require the development of suitable materials that have good conductivity, remain solid at high temperature, chemically compatible with other cell components, dimensionally stable.
- Have a moderate intolerance to sulfur.
- Do not yet have practical fabrication processes.

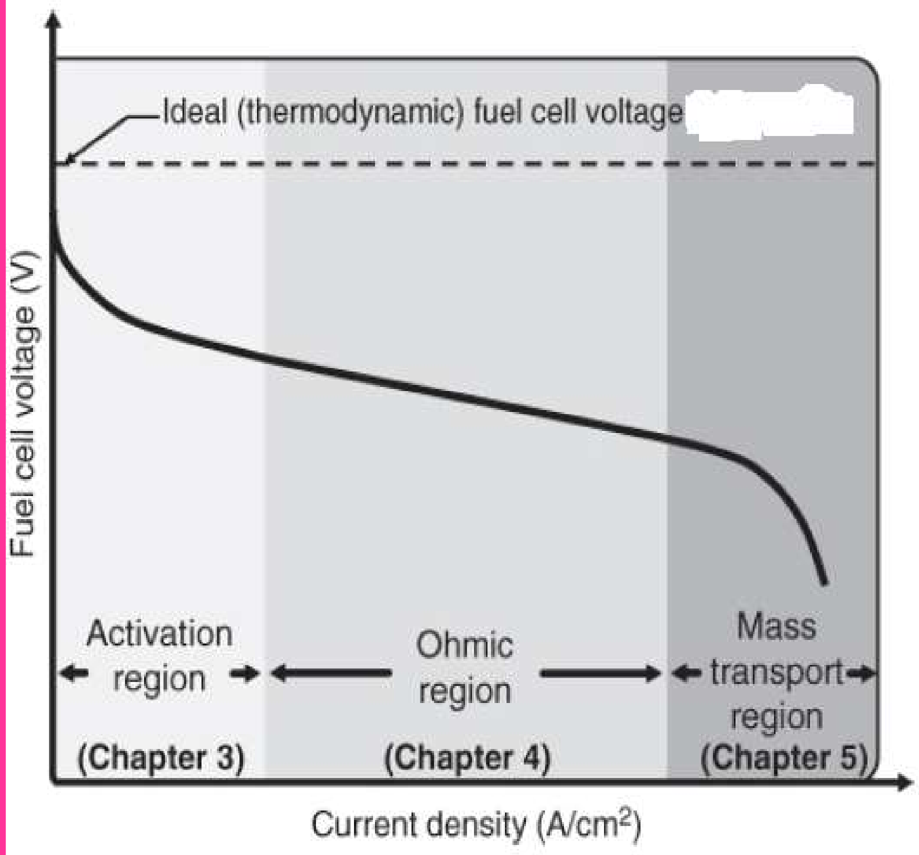
OBSTACLES FOR FUEL CELLS

- Lack of a hydrogen infrastructure. Fuel must be readily available.
- Storage i.e., Storing H_2 in pressure tanks and high-pressure tanks are very expensive. Fuel cell vehicle stores H_2 at 5,000 psi has a driving range of 150 miles. Doubling the pressure would nearly double the driving range.
- Some FCEVs have on-board reformers that extract H_2 from gasoline, ethanol/methanol. Storing these fuels requires less space & is much simpler than storing pure H_2.
- Reformer are expensive and has undesirable emissions such as CO_2 & does not reduce dependence on fossil fuels.
- Reformers require long time before they can provide enough hydrogen to move a vehicle a few feet.
- Cost of a fuel cell and its supporting systems is extremely high.

OBSTACLES FOR FUEL CELLS

- FCEVs are too quiet. Vehicles can be seen but not heard, their approach to the rear of pedestrians and bicyclists can present dangerous situations.
- Most fuel cells take some time to start, especially when they are cold.
- Fuel cell does not generate electricity until it has a temperature of 0˚C.
- Fuel cells become very hot while they operate. Typically PEM cell requires larger radiators & needed more space just for the cooling system results in less useable space for passengers and luggage.
- Solid oxide fuel cell operates 700 - 1,000˚C. If heat is not totally insulated from the passenger compartment, it could bake everyone and everything inside the vehicle.

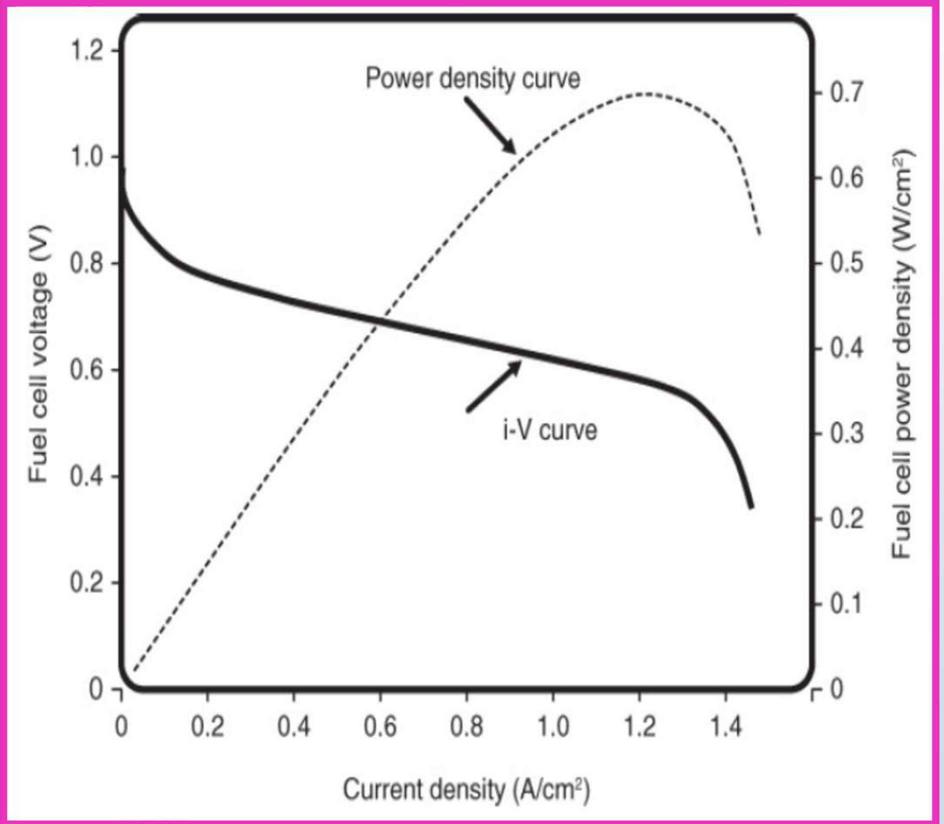
POTENTIAL & i-V CURVE or PERFORMANCE OF FUEL CELLS



Schematic of fuel cell *i*–*V* curve.

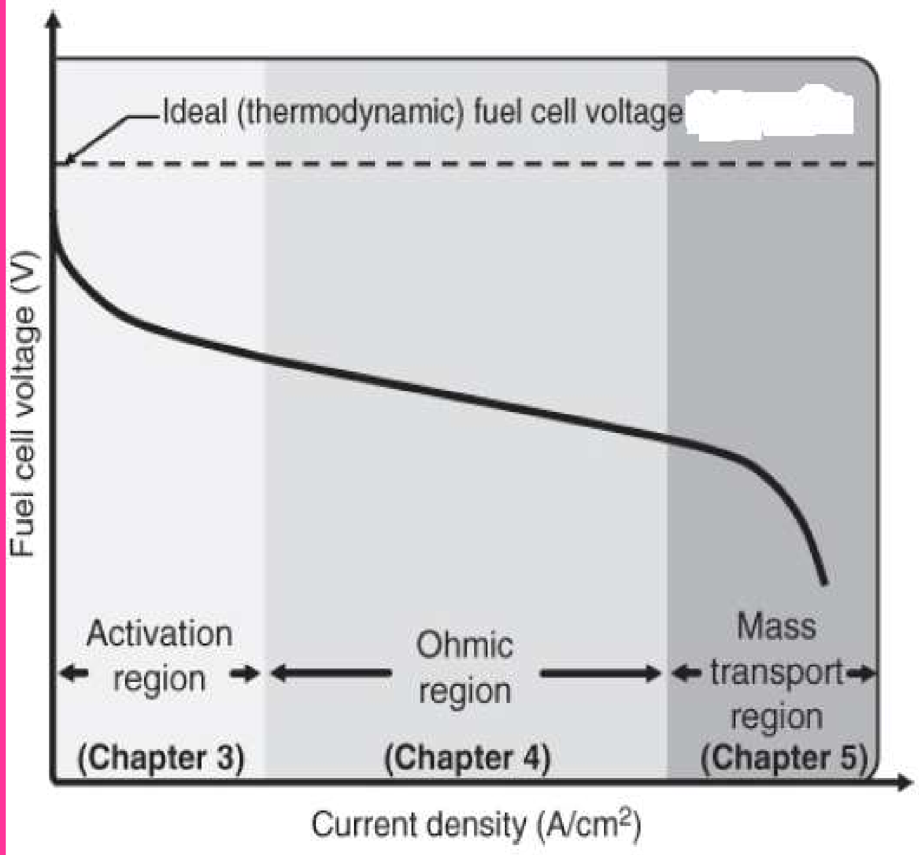
- Current–voltage (i-V) curve, shows the voltage output of fuel cell for a given current output.
- As larger FC can produce more electricity than a smaller FC, curves are normalized by FC area (Current density) to make results comparable.
- An ideal FC would supply any amount of current as long as it is supplied with fuel, while maintaining a constant voltage determined by thermodynamics.
- In practice, actual voltage output of a real FC is less than ideal thermodynamically predicted voltage.
- More current that is drawn from a real FC, lower voltage output of cell, limiting the power (p=iV) delivered.

POWER DENSITY CURVE or PERFORMANCE OF FUEL CELLS



- **Power density curve is constructed from *i–V* curve by multiplying voltage at each point on *i–V* curve by the corresponding current density.**
- **FC power density increases with increasing current density, reaches a maximum then falls at still higher current densities.**
- **FCs are designed to operate at or below power density maximum.**
- **At current densities below the power density maximum, voltage efficiency improves but power density falls.**
- **At current densities above the power density maximum, both voltage efficiency and power density fall.**
- **Current supplied by a FC is directly proportional to amount of fuel consumed.**
- **Therefore, as FC voltage decreases, electric power produced *per unit of fuel* also decreases.**

POWER DENSITY CURVE or PERFORMANCE OF FUEL CELLS

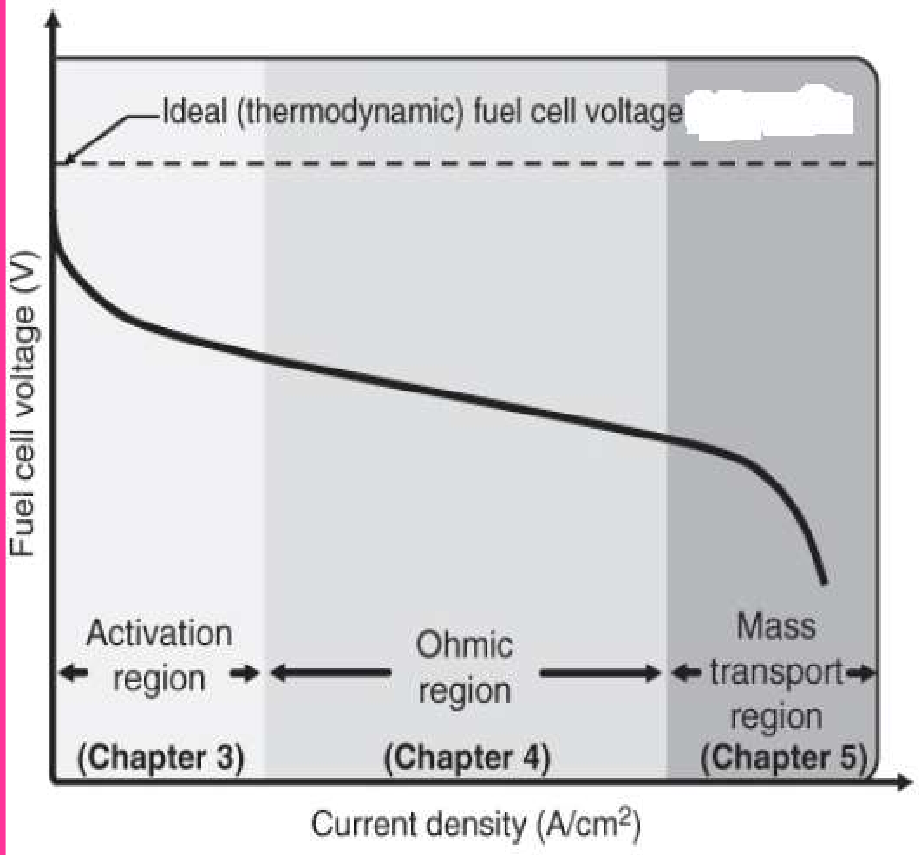


Schematic of fuel cell *i*–*V* curve.

- Voltage output of a real FC is less than thermodynamically predicted voltage output due to irreversible losses.
- More current that is drawn from cell, the greater these losses.
- Three major types of fuel cell losses,
- 1. Activation losses (losses due to electrochemical reaction)
- 2. Ohmic losses (losses due to ionic and electronic conduction)
- 3. Concentration losses (losses due to mass transport)
- Real voltage output for a FC is the thermodynamically predicted voltage output of FC and subtracting voltage drops due to various losses.

$$V = E_{thermo} - \eta_{act} - \eta_{ohmic} - \eta_{conc}$$

POWER DENSITY CURVE or PERFORMANCE OF FUEL CELLS



Schematic of fuel cell *i*–*V* curve.

- **Activation losses mostly affect initial part of the curve**
- **Ohmic losses are most apparent in the middle section of the curve**
- **Concentration losses are most significant in the tail of the i-V curve.**

FUEL CELL EFFICIENCY

- For any energy conversion device, efficiency is of great importance.

- 1. "ideal" (or reversible) efficiency 2. "real" (or practical) efficiency.

- Tempted to think that the ideal efficiency of a FC should be 100%, this is not true.

- From Thermodynamics, electrical work available from a FC is limited by ΔG (Gibbs function), ideal efficiency of FC is also limited by ΔG.

- A real FC must always be less efficient than an ideal fuel cell as real FC incur nonideal irreversible losses during operation.

FUEL CELL EFFICIENCY

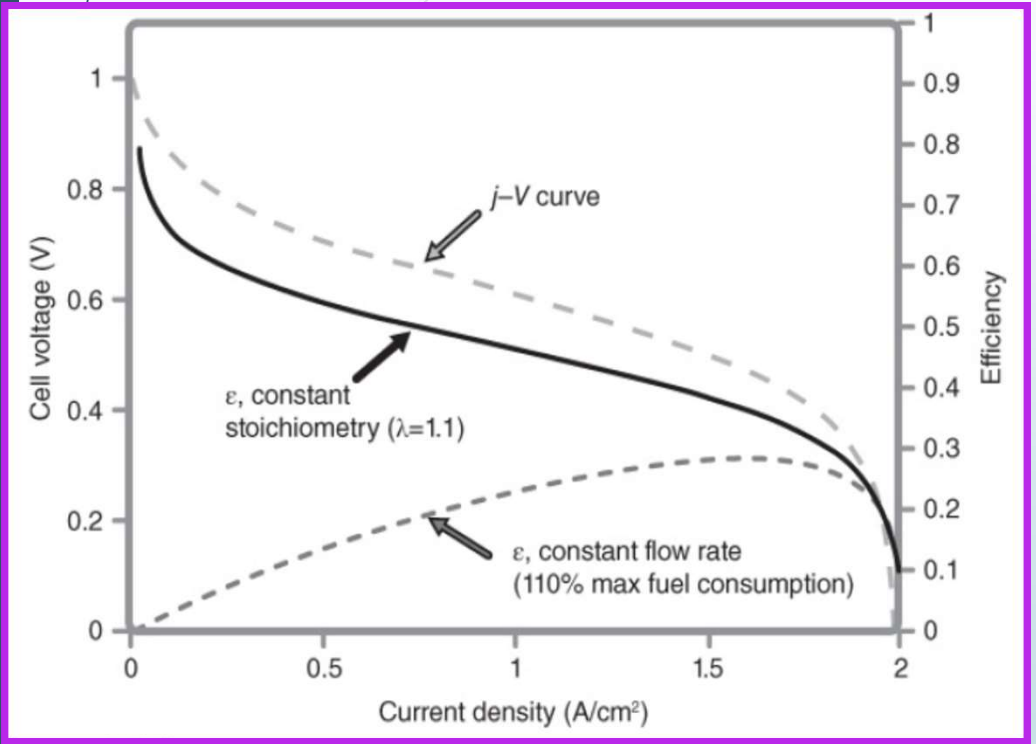
- **Efficiency (ε) : The amount of useful energy that can be extracted from the process relative to total energy evolved by that process**
- $$\varepsilon = \frac{\text{Useful Energy}}{\text{Total Energy}}$$
- For FC, $\varepsilon = \frac{\text{Max. energy available to do work } (\Delta g)}{\text{Total Energy } (\Delta h)}$

Δg = Gibbs free energy

- For H_2 FC Δg = - 237.17 kJ/mol & $\Delta h_{HHV} = -288.83$ kJ/mol

$\varepsilon_{thermo,\ FC} = 0.83$

FUEL CELL EFFICIENCY



- Under a constant-stoichiometry condition, FC efficiency curve follows the fuel cell *i*–*V* curve. Efficiency is highest at low current density.

- Under a constant-flow-rate condition (110% of rate required at maximum current), FC efficiency is poor at low current densities (because most of the fuel is wasted) & reaches a maximum at high current densities when most of the fuel is used.

FUEL & OXIDANT CONSUMPTION

- Fuel and oxidant consumptions are proportional to current drawn from fuel cell.
- Chemical reaction in fuel cell $A + x_B B \longrightarrow x_C C + x_D D$

  Where A – fuel; B – oxidant; C & D – Products

- Mass flow of the fuel associated with current drawn from fuel cell

$$m_A = \frac{W_A I}{1000\, nF} \text{ in kg/s}$$

W_A – mole. wt of fuel; I – current drawn form FC; n – e^- transferred in the reaction; F = Faraday's constant = 96495 C/mol

- Stoichiometric ratio of oxidant mass flow to fuel mass flow

$$\frac{m_B}{m_A} = \frac{x_B w_B}{w_A}$$

FUEL & OXIDANT CONSUMPTION

- For H_2 FC, stoichiometric ratio is

$$\frac{m_H}{m_0} = \frac{0 \cdot 5w_0}{w_H} = \frac{0.5 \times 32}{2.016} = 7.937$$

$$\lambda = \frac{(\dot{m}_B/\dot{m}_A)_{actual}}{(\dot{m}_B/\dot{m}_A)_{stoi}}.$$

- Equivalent ratio (λ) of oxidant to fuel is defined as the ratio of the actual oxidant/fuel ratio to the stoichiometric ratio.

- When $\lambda > 1$, the reaction is fuel rich; when $\lambda = 1$, the reaction is stoichiometric; and when $\lambda < 1$, the reaction is fuel lean.

- In practice, fuel cells are always operated at $\lambda > 1$, rich mixture is supplied to reduce the voltage drop caused by concentration.

FUEL CELL SYSTEM CHARACTERISTICS

- FCs need auxiliaries include air circulating pump, coolant circulating pump, ventilation fan, fuel supply pump & electrical control devices to support their operation.
- Among this air circulating pump is the largest energy consumer.
- Power consumed by air circulating pump may take about 10% of total power output of FC stack.
- In FC, air pressure on the electrode surface p, is usually higher than atm. pressure p_0, in order to reduce the voltage drop.

FUEL CELL MAINTENANCE

Fuel Cell Engine Warnings and Cautions:

- **Wait at least five minutes after engine is shut down prior to servicing any fuel cell engine component in order to discharge any residual electrical charge from FC stacks.**

- **Ensure that stack voltmeters indicate 0V DC prior to servicing any FC engine component.**

- **Always use a hand-held voltmeter to ensure that a given stack is at 0V DC prior to servicing stack.**

- **Take care when handling FC engine components to prevent damage.**

FUEL CELL MAINTENANCE

Fuel Cell Engine Warnings and Cautions:

- **Some FC stack components are fragile. Follow documented procedures when handling stacks to prevent damage.**
- **Keep foreign objects, materials, petroleum-based products, oil and grease away from FC stacks or any FC engine components that pass fuel, air or coolant to or from FC stacks. Doing so may destroy FC stacks.**
- **Never introduce any leak inhibitors or other foreign sub-stances into water system. Doing so may destroy the fuel cell stacks.**
- **Replace all non-rubber gaskets once used. Replace rubber gaskets during maintenance if they have been in service for six months or if damaged.**

FUEL CELL MAINTENANCE

Fuel Storage System (Rooftop) Warnings and Cautions:

- **Whenever possible, access rooftop components while parked indoors. If outdoors, latch the canopies open. Canopies can suddenly close when exposed to wind.**
- **Access rooftop components by opening one canopy and standing on the opposite (closed) canopy.**
- **Where available, wear a personal safety harness and attach it to an overhead safety cable when on the bus roof.**
- **Never open or tighten any high-pressure fitting or component without first venting H_2 & verifying that *all* high-pressure gauges or displays indicates 10 psig or less. This ensures that high-pressure circuit is depressurized even if one of the gauges indicates an incorrect value.**
- **All personnel working with H_2 storage components must have high pressure gas training or high pressure gas certification.**
- **Close fuel shutoff valve that supplies fuel to engine only in case of emergency. Closing the valve during operation can damage FC stacks.**

FUEL CELL MAINTENANCE

Fuel Storage System (Rooftop) Warnings and Cautions:

- Instead, turn off the engine in order to automatically close the solenoid valves associated with each H_2 cylinder and high-pressure manifold; this isolates all fuel within the fuel storage system.
- Take care when handling fuel storage system components to prevent damage.
- Do not walk on cylinders. Do not expose cylinders to any form of abrasion. Protect cylinders from tool impact. Do not expose cylinders to corrosive acids or bases, or add coatings.
- Do not leave tools or other items on the roof.
- Do not step on roof covers or hatches.

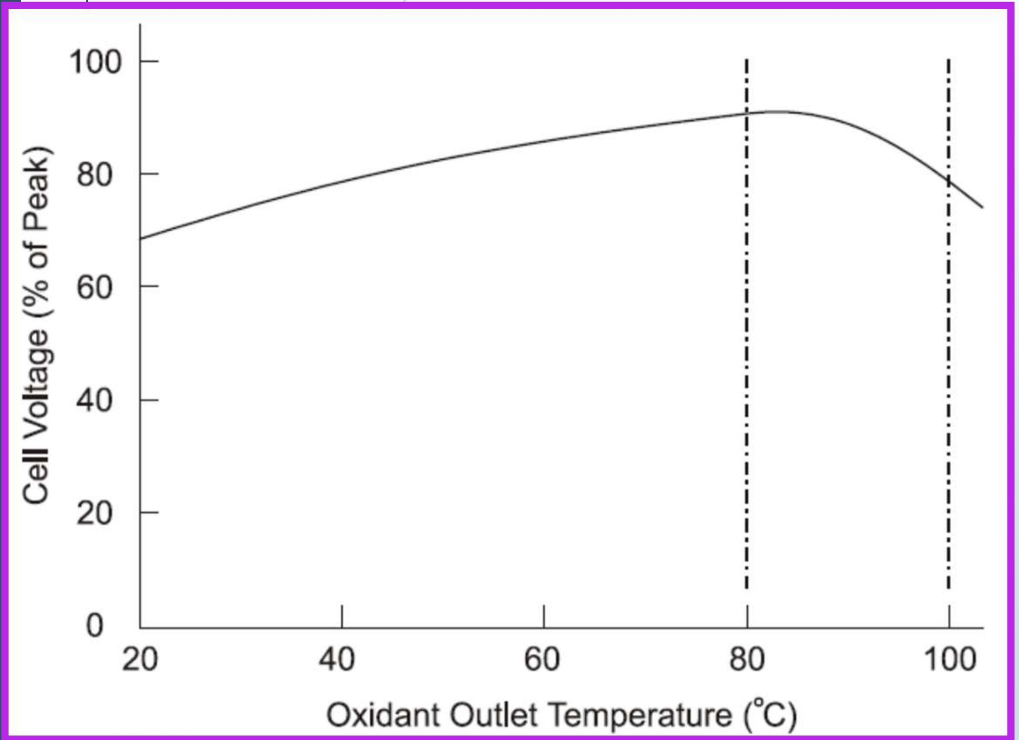
FACTORS AFFECTING FUEL CELL CHARACTERISTICS

- Temperature effect
- Pressure effect
- Stoichiometry effect
- Humidity effect

FACTORS AFFECTING FUEL CELL CHARACTERISTICS:
Pressure Effect

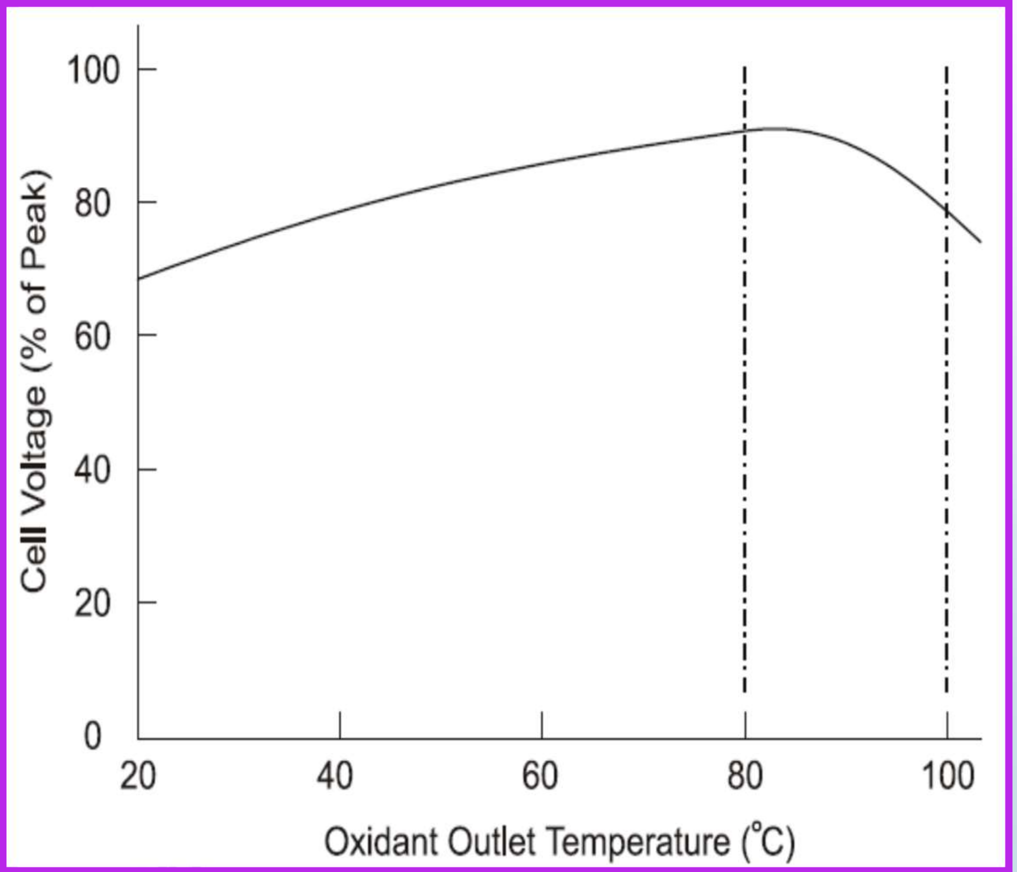
- FC polarization curves increase with increasing operating pressure.
- Rate of chemical reaction is proportional to partial pressures of H_2 & O_2.
- Effect of increased pressure is most prominent when using a dilute oxidant (like air) or a dilute fuel (like reformate).
- Higher pressures help to force H_2 & O_2 into contact with electrolyte.
- Although an increase in pressure promotes electro-chemical reaction, it introduces other problems.
- FC stack flow field plates work better at low pressure since they exhibit smaller flow induced pressure losses.
- FC seals operate under additional stress.
- Additional air compression is required, which absorbs more power.

FACTORS AFFECTING FUEL CELL CHARACTERISTICS: Temperature Effect



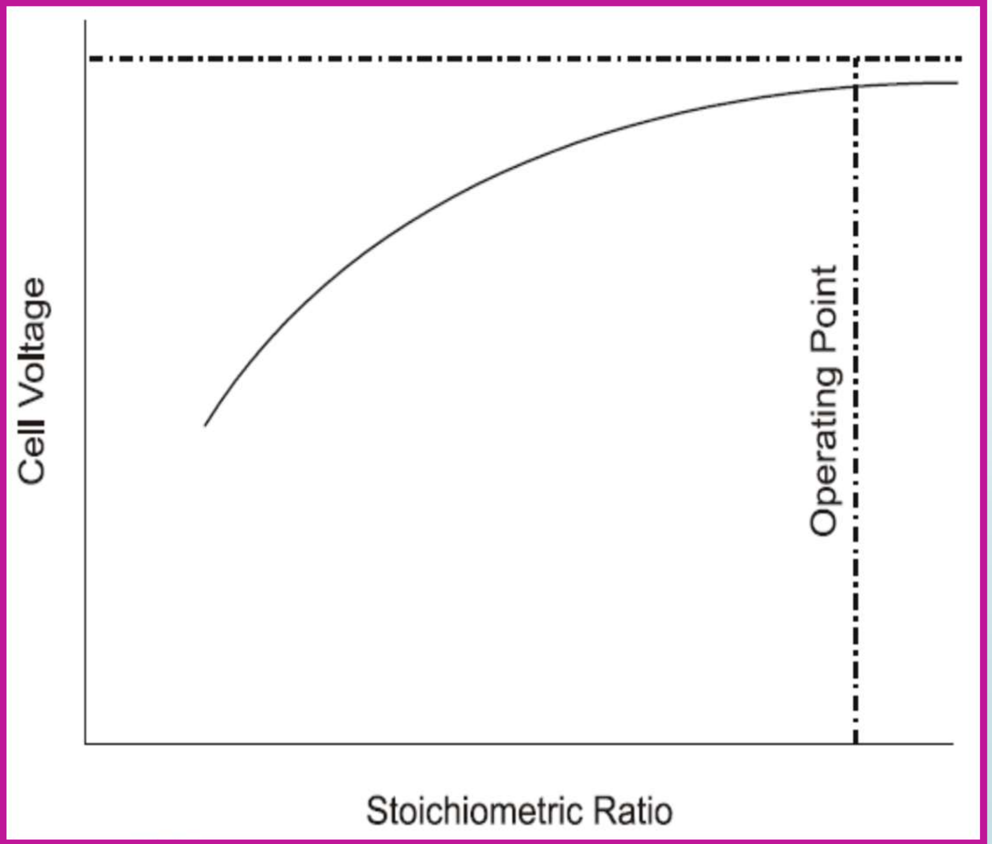
- FC polarization curves increase with increasing operating temperature.
- Higher temperatures improve mass transfer within FC.
- As the temperature increases, electronic conduction in metals decreases but the ionic conduction in the electrolyte increases.
- Accumulation of product water within the oxidant stream effectively limits operating temperatures to below 100˚C.
- At 100˚C, water boils and the resulting steam severely reduces partial pressure of O_2. This, in turn, drastically reduces cell performance due to s O_2 starvation & can damage FC.

FACTORS AFFECTING FUEL CELL CHARACTERISTICS:
Temperature Effect



- Higher temperatures can be achieved by operating at higher pressures since this increases the water boiling point accordingly.
- Net effect is that FC voltage increases with temperature until temperature approaches boiling point of water at which the voltage begins to decline.
- Optimum temperature occurs near 80°C where the two effects balance each other.

FACTORS AFFECTING FUEL CELL CHARACTERISTICS: Stoichiometry Effect



- Stoichiometry is the ratio of the amount of gas present relative to the amount of that gas that is needed to exactly complete the reaction.
- FC polarization curves increase with increasing reactant stoichiometry.
- Higher stoichiometry increases the chance that sufficient numbers of H_2 & O_2 molecules interact with electrolyte.
- Insufficient stoichiometry "starves" the FC stack of sufficient reactants and may cause permanent damage.
- Stoichiometric ratio of 1.0 provides exactly the correct number of gas molecules to theoretically complete the reaction.
- Stoichiometric ratio greater than 1.0 provide excess gas and ratios less than 1.0 provide insufficient gas.

FACTORS AFFECTING FUEL CELL CHARACTERISTICS: Humidity Effect

- Gas stream humidification is essential to FC operation since water molecules move with H+ ions during ion exchange reaction.
- Insufficient humidification water dehydrates membrane and can lead to cracks or holes in the membrane results in a chemical short circuit, local gas mixing, hot spots, and possibility of fire.
- Conversely, excess humidification water leads to condensation and flooding within the flow field plates, result in a phenomenon known as cell reversal where the affected cells produce a zero or negative voltage.
- If a large enough negative voltage occurs, the affected FC start to act like an electrolyzer. This produces a lot of heat and can potentially destroy the cell.
- Humidifier water must remain non-conductive. Failure to do so causes short circuits and corrosion currents within the fuel cell stack. Water becomes conductive as it absorbs ions from its surroundings. To eliminate these ions, the water must continuously flow through a de-ionizing filter.

DURABILITY OF FUEL CELL

- Durability target for FC components is closely related to specific application, e.g. buses and passenger vehicles need to have a durability of 20 000 h & 5 000h, respectively.

- Lifetime of FC is dependent on lifetime of the membrane.

- As membrane failure not only implies a decrease in performance, but is equivalent to end-of-life of FC.

- Three main degradation mechanisms affecting the membrane durability are: i) Chemical degradation ii) Mechanical degradation iii) Thermal degradation

DURABILITY OF FUEL CELL

- Chemical degradation refers to the attack of the polymer chains and end-groups
- Chemical degradation leads to membrane thinning.
- It is highly probable that chemical degradation of the membrane is present during Start-ups and Shut-downs
- Mechanical degradation occurs when membrane experiences creep, cracking or formation of pinholes.
- Possible causes for this type of degradation are many, e.g. fabrication defects, improper MEA assembly by the seals, edges or by inhomogeneous compression of bi-polar plates.

DURABILITY OF FUEL CELL

- Thermal degradation occurs at high temperatures.
- Above 200 ˚C , loss of sulfonate groups begins to occur.
- Consequently, during normal FC operating temperatures (below 100˚C), thermal decomposition of membrane is often neglected.