Energy Storage Systems

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Lecture 1

- Different types energy storage
- Basic requirement of EV & HEVs
- Basics about energy storage
- Energy source used for EV’s & HEV’s

Different types energy storage

- **Compressed Air Storage**
- **Pumped-Storage Hydroelectricity**
- **Advanced Rail Energy Storage**
- **Flywheel Energy Storage**
- **Battery Storage (used in EV/HEV applications)**
- **Liquid Air Energy Storage**
- **Pumped Heat Electrical Storage**
- **Redox Flow Batteries**
- **Superconducting Magnetic Energy Storage**
- **Methane**

EV/HEV Performance Requirements in terms of battery

- Hybrid vehicles
  - High power density
  - High power delivery for acceleration
  - Adequate energy density
  - Wide ambient temperature range

- Electric vehicles
  - High energy density
  - Fast, reliable charging

Electrochemical Energy Storage.

Battery requirements for EV applications should include:

- Energy storage large enough to ensure a desired driving range.
- Input power capability that is high enough to give good acceleration, good regenerative braking for achieving high-energy efficiency, and to accept fast charge for vehicle convenience.
- Life that is long enough to meet the general standard of automotive component life.
- Durability against environmental demands (e.g. climatic stress, mechanical stress, etc) so that EVs may work in harsh environment where conventional vehicles should normally work.
- Abuse tolerance to keep battery safe under extreme conditions (e.g. overcharge, internal short-circuits, etc).

What is battery?

- Battery is a type of Energy storage system, which converts chemical energy into electrical energy.
- Battery is made up of 2 or more cells , connected in such a way to produce the required amount of power/energy.
- For EV/HEV its essential to know as fundamental preparation for knowing how to use cell/battery optimally in an application.

cell

- Cells are the smallest individual electrochemical unit, and deliver a voltage that depends on the cell chemistry.
- There are primary (single use) and secondary (rechargeable) cells.
- A cell is different from a battery

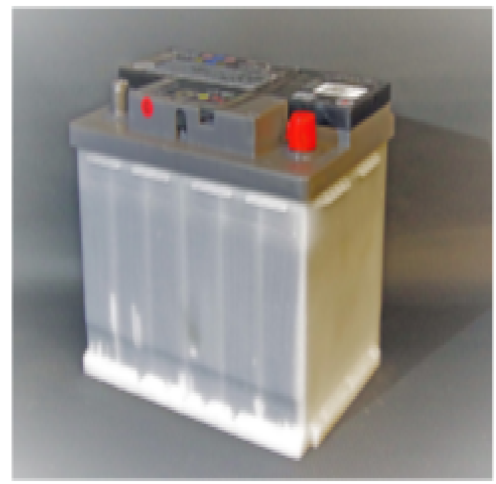
Some example electrochemical cells

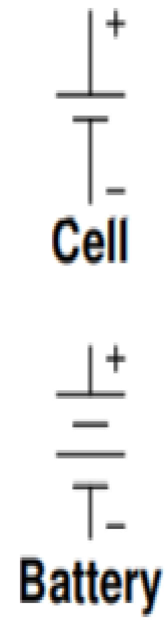
- The table below shows components for commonly used electrochemical cells:

Electrochemistry	Negative electrode	Positive electrode	Electrolyte	Nominal voltage
Lead acid	Pb	PbO_2	H_2SO_4	2.1 V
Dry cell	Zn	MnO_2	$ZnCl_2$	1.6 V
Alkaline	Zn	MnO_2	KOH	1.5 V
Nickel cadmium	Cd	NiOOH	KOH	1.35 V
Nickel zinc	Zn	NiOOH	KOH	1.73 V
Zinc air	Zn	O_2	KOH	1.65 V

batteries

- Batteries and battery packs are made up from groups of cells
  - These cells can be wired together in series, in parallel, or in some combination of both
  - Sometimes they are packaged in a single physical unit
    - For example, automotive 12 V lead-acid batteries comprise six 2 V cells in series
  - Other times, the connections are external to the cells
- We use schematic symbols to represent cells and batteries in a circuit diagram.





Energy Storage(Batteries)

- A battery consists of two or more electric cells joined together.
- The cells convert chemical energy to electrical energy.
- The cells consist of positive and negative electrodes joined by an electrolyte.
- It is the chemical reaction between the electrodes and the electrolyte which generates DC electricity.
- In the case of secondary or rechargeable batteries, the chemical reaction can be reversed by reversing the current and the battery returned to a charged state
- The ‘lead acid’ battery is the most well known rechargeable type
- The first electric vehicle using rechargeable batteries preceded the invention of the rechargeable lead acid by quarter of a century
- There are a very large number of materials and electrolytes that can be combined to form a battery. However, only a relatively small number of combinations have been developed as commercial rechargeable electric batteries suitable for use in

Batteries suitable for use in vehicles (Rechargeable)

- Lead acid batteries
- Lithium ion batteries
- Metal air batteries
- Nickel iron
- Nickel cadmium
- Nickel metal hydride
- Sodium sulphur and sodium metal chloride.

Overview of Batteries

From the electric vehicle designer's point of view the battery can be treated as a 'black box' which has a range of performance criteria. These criteria will include:

- specific energy
- energy density
- specific power
- typical voltages
- amp hour efficiency
- energy efficiency
- commercial availability
- cost
- operating temperatures
- self-discharge rates
- number of life cycles
- recharge rates

Overview of batteries(designer point of view for EV/HEV Applications)

The designer also needs to understand how energy availability varies with regard to:

ambient temperature

charge and discharge rates

battery geometry

optimum temperature

charging methods

cooling needs.

However, at least a basic understanding of the battery chemistry is very important, otherwise the performance and maintenance requirements of the different types, and most of the disappointments connected with battery use, such as their limited life, self discharge, reduced efficiency at higher currents.

Energy Storage Systems

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Battery Performance Characteristics

BATTERY PARAMETERS:

- Battery Capacity
- Open circuit& terminal voltages
- SOC
- SD
- DOD
- Energy Density
- power density
- Specific energy
- Specific Power

Battery Capacity

- The capacity of a battery system is the measure of the amount of free charge generated by the active material at the negative electrode and consumed by the positive electrode.
- This parameter is measured in Coulombs (C)
- It is generally expressed in Ampere-hour (Ah)
- where 1Ah = 3600C

Ah of a battery system which is sometimes denoted by the letter ‘C’ corresponding to the coulometric capacity, is specified under constant current discharge.

Ideally, the Ah rating for a specific battery would be the same for any discharge current.

Practically, actual capacity is dependent on the magnitude of the discharge current

For example, a 20Ah battery could be rated to deliver 1A for 20 hours but instead would not be able to deliver 20A for a complete 1-hour duration

Energy stored

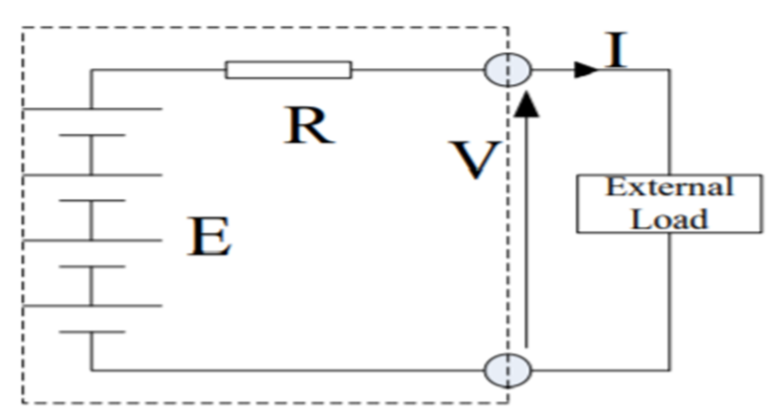
- The energy stored in a battery depends on its voltage, and the charge stored.
- The SI unit is the Joule, but this is an inconveniently small unit
- Unit- Whr

$$Energy\ in\ Whr = V \times Ahr$$

Open circuit& terminal voltages

- All electric cells have nominal voltages which gives the approximate voltage when the cell is delivering electrical power.
- The cells can be connected in series to give the overall voltage required.
- V=Terminal voltage
- E= Nominal voltage
- R=internal resistance

$$V = E - IR$$



Simple equivalent circuit model of a battery.

Self-discharge rates(SD)

The rate at which battery discharges when unused

- Most batteries discharge when left unused, and this is known as self-discharge
- This is important as it means some batteries cannot be left for long periods without recharging
- The rate varies with battery type, and with other factors such as temperature
- higher temperatures greatly increase self-discharge

SOC & DOD

- State of charge (SoC) is the level of charge of an electric battery relative to its capacity

The units of SoC are percentage points (0% = empty; 100% = full)

SoC is normally used when discussing the current state of a battery in use

- Depth of discharge (DoD): An alternative form of the same measure

It is the the inverse of SoC (100% = empty; 0% = full).

DoD is most often seen when discussing the lifetime of the battery after repeated use.

Energy density

- The **battery energy density** is the proportion of **energy** that can be included in a particular unit (mass or capacity)
- Energy density is the amount of electrical energy stored per cubic metre of battery volume.
- It normally has units of Wh.m−3

Power density

- **Power density** is the amount of **power** per unit volume.
- In **energy** transformers including **batteries**, fuel cells, motors, etc., and also **power** supply units or similar, **power density** refers to a volume.
- It is then also called volume **power density**, which is expressed as W/m^3.
- **In SI base units:** $kg \cdot m^{-1} s^{-3}$
- **SI unit:** W/m^3

Charge and Discharge rates(**C rate)**

- The C-rate is a measure of the rate at which a battery is being charged or discharged
- It is defined as the current through the battery divided by the theoretical current draw under which the battery would deliver its nominal rated capacity in one hour
- It has the units h^{-1}
- C-rate is used as a rating on batteries to indicate the maximum current that a battery can safely deliver on a circuit
- Standards for rechargeable batteries generally rate the capacity over a 4-hour, 8 hour or longer discharge time

Battery Specific Energy (SEbatt)

- Specific energy is the amount of electrical energy stored for every kilogram of battery mass. It has units of $Wh.kg^{-1}$.
- The amount of energy per unit of battery mass is termed as the specific energy of battery
- expressed in watt-hour per kilogram (Wh/kg). serves as an approximation of the energy deliverable from a battery
- commonly used as a reference quantifier between classes of battery technology
- The actual energy that can be extracted from a battery system depends on several factors such as the temperature and discharge rate.
- As a general expression, the battery specific energy is
- Since the discharge energy varies with the discharge rate of the battery, the specific energy of the battery also varies accordingly.

$$SE_{batt} = \frac{\text{Discharge Energy}}{\text{Total Battery Mass}} = \frac{E_{dis}}{M_{batt}}$$

Battery Specific Power (SPbatt)

- Specific power is the amount of power obtained per kilogram of battery. It is a highly variable and rather anomalous quantity, since the power given out by the battery depends far more upon the load connected to it than the battery itself.
- The specific power of a battery system is the parameter that quantifies the magnitude of power obtainable per unit mass
- Expressed in watt per kilogram (W/kg)
- serves as an approximation of the power level available from a battery system

$$SP_{batt} = \frac{\text{Discharge Power}}{\text{Total Battery Mass}} = \frac{P_{dis}}{M_{batt}}$$

Energy Storage Systems

Batteries suitable for use in vehicles(Rechargeable)

- Lead acid batteries
- Lithium ion batteries
- Metal air batteries
- nickel iron
- nickel cadmium
- nickel metal hydride
- sodium sulphur and sodium metal chloride.

Comparison of batteries as per current EV technology

	Lead Acid	Nickel metal hydride	Sodium Metal Chloride
Specific Energy	20-35 Wh/kg	~65 Wh/kg	100 Wh/kg
Energy Density	54-95 Wh/l	~150 Wh/l	120 Wh/l
Specific Power	~250 W/kg	200 W/kg	150 W/kg
Nominal Cell Voltage	2V	1.2V	~2V (2.5 when fully charged)
Amphour efficiency	~80% (temp dependent)	>80%	>80%
Internal resistance	~0.022 ohm per cell @ 1Ah/cell	~0.06 ohm per cell @ 1Ah/cell	High at low SoC
Operating temperature	Ambient (poor in extreme cold)	Ambient (~25deg C)	300 - 350 deg C
Self-discharge	~2% per day	~5% per day	~10%
Number of Cycles	~800	~1000	>1000
Recharge time	8h (90% in 1 hour possible)	1hour rapid charge	2-3 hours

Comparison of batteries as per current EV technology

	Lithium Ion	Aluminium Air	Zinc Air
Specific Energy	180 Wh/kg	225 Wh/kg	230 Wh/kg
Energy Density	153 Wh/l	195 Wh/l	270 Wh/l
Specific Power	300 W/kg	10 W/kg	105 W/kg
Nominal Cell Voltage	3.5 V	1.4 V	1.2 V
Amphour efficiency	>80%	N/A	N/A
Internal resistance	Very Low	Very High	Medium
Operating temperature	Ambient (~25deg C)	Ambient (~25deg C)	Ambient (~25deg C)
Self-discharge	Very Low (~ 10% per month)	>10% per day	High
Number of Cycles	>1000	>1000	>2000
Recharge time	2 - 3h	10 mins (to replace electrode)	10 mins (to replace electrode)

Lead Acid Batteries

Advantages: Lead-acid batteries have been the most popular choice of batteries for EVs.

- Lead-acid batteries can be designed to be high powered and are inexpensive, safe, and reliable. Relatively low cost • Easy availability of raw materials (lead, sulphur) • Ease of manufacture • Favorable electromechanical characteristics ,A recycling infrastructure is in place for them

Disadvantages: low specific energy, poor cold temperature performance, and short calendar and cycle life are among the obstacles to their use in EVs and HEVs.

CELL DISCHARGE OPERATION(PBA)

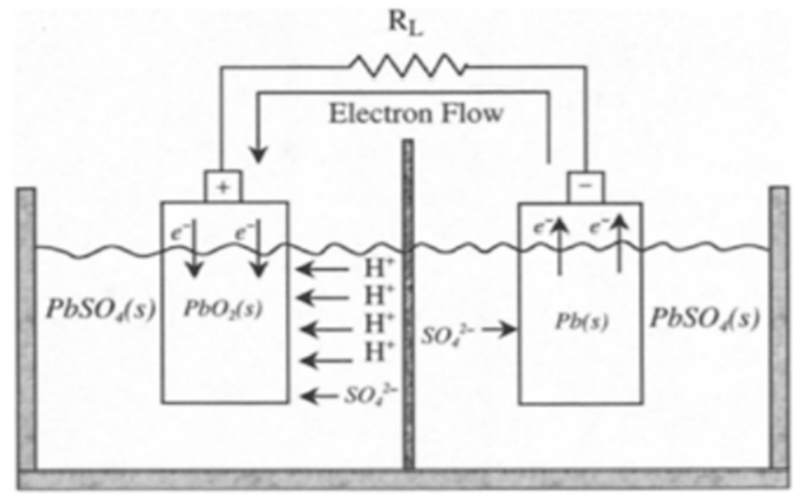
In the cell discharge operation ,electrons are consumed at the positive electrode, the supply of which comes from the negative electrode. The current flow is, therefore, out of the positive electrode into the motor-load, with the battery acting as the sou

The positive electrode equation is given by:

$$PbO_2(s) + 4H^+(aq) + SO_4^{2-}(aq) + 2e \rightarrow PbSO_4 + 2H_2O(l)$$

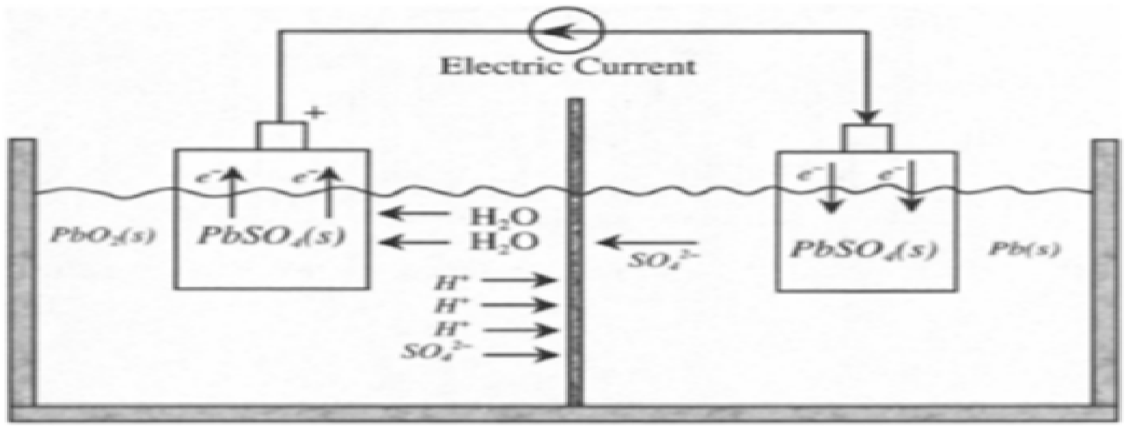
The negative electrode equation during cell discharge is:

$$Pb(s) + SO_4^{2-}(aq) \rightarrow PbSO_4 + 2e$$



Lead-acid battery: cell discharge operation.

CELL CHARGE OPERATION(PBA)



Lead-acid battery: cell charge operation.

$$PbSO_4(s) + 2H_2O(l) \rightarrow PbO_2(s) + 4H^+(aq) + SO_4^{2-}(aq) + 2e$$

The chemical reaction at the negative electrode during cell charging is:

$$PbSO_4(s) + 2e \rightarrow Pb(s) + SO_4^{2-}(aq)$$

The overall chemical reaction during cell charging is:

$$2PbSO_4(s) + 2H_2O(l) \rightarrow Pb(s) + PbO_2(s) + 2H_2SO_4(aq)$$

NICKEL-CADMIUM BATTERY

The NiCd battery employs

positive electrode: nickel oxide

negative electrode : metallic cadmium

Electrolyte: the potassium hydroxide (KOH)

The net reaction occurring in the potassium hydroxide (KOH) electrolyte is:

$$Cd + 2NiOOH + 2H_2O \underset{Charge}{\overset{Discharge}{\rightleftarrows}} 2Ni(OH)_2 + Cd(OH)_2 \text{ (1.299 volts)}$$

NICKEL-METAL-HYDRIDE (NiMH) BATTERY

positive electrode -nickel oxide similar to that used in a NiCd battery

negative electrode -metal hydride where hydrogen is stored.

The concept of NiMH batteries is based on the fact that fine particles of certain metallic alloys, when exposed to hydrogen at certain pressures and temperatures, absorb large quantities of the gas to form the metalhydride compounds. Furthermore, the metal hydrides are able to absorb and release hydrogen many times without deterioration. The two electrode chemical reactions in a NiMH battery are:

M stands for metallic alloy, which takes up hydrogen at ambient temperature to form the metal hydride MHX

At the positive electrode,

$$NiOOH + H_2O + e^- \underset{Charge}{\overset{Discharge}{\rightleftarrows}} Ni(OH)_2 + OH^-$$

At the negative electrode,

$$MH_x + OH^- \underset{Charge}{\overset{Discharge}{\rightleftarrows}} MH_{x-1} + H_2O + e^-$$

Advantages & disadvantages

Advantages:

much longer life cycle than lead-acid batteries safe and abuse tolerant.

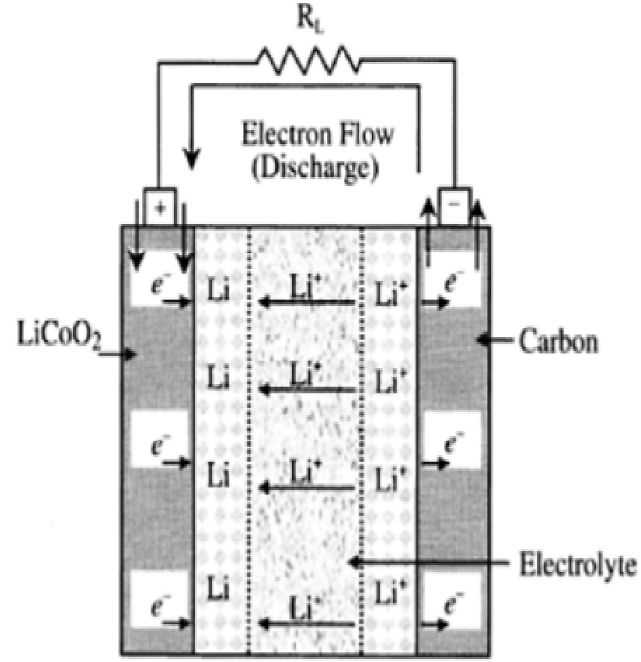
Disadvantages:

high cost, higher self-discharge rate compared to NiCd, poor charge acceptance capability at elevated temperatures, and low cell efficiency.

NiMH is likely to survive as the leading rechargeable battery in the future for traction applications

LI-ION BATTERY

- During cell charge operation, lithium ions move in the opposite direction from the positive electrode to the negative electrode.
- The nominal cell voltage for a Li-ion battery is 3.6 V, which is equivalent to three NiMH or NiCd battery cells.
- Lithium-ion batteries have high specific energy, high specific power, high energy efficiency, good high-temperature performance, and low self-discharge.
- The components of Li-ion batteries are also recyclable.
- These characteristics make Li-ion batteries highly suitable for EV and HEV and other applications of rechargeable batteries.



At the positive electrode,

$$xLi^+ + xe^- + Li_{(1-x)}CoO_2 \underset{Charge}{\overset{Discharge}{\rightleftarrows}} LiCoO_2$$

EV Battery Technology , Classification and Overal Reaction

Battery Technology	Type Classification	Overall Chemical Reaction
Lead Acid	Valve Regulated Lead Acid (VRLA)	$Pb + PbO_2 + 2H_2SO_4 \leftrightarrow 2PbSO_4 + 2H_2O$
Nickel Based	Nickel Cadmium (Ni-Cd)	$Cd + 2NiOOH + 2H_2O \leftrightarrow CD(OH)_2 + 2Ni(OH)_2$
	Nickel Zinc (Ni-Zn)	$Zn + 2NiOOH + 2H_2O \leftrightarrow Zn(OH)_2 + 2Ni(OH)_2$
	Nickel Metal Hydride (Ni-MH)	$MH + NiOOH \leftrightarrow M + Ni(OH)_2$
Metal-Air Based	Zinc Air (Zn/Air)	$2Zn + O_2 \rightarrow 2ZnO$
	Aluminium Air (Al/Air)	$4Al + 3O_2 + 6H_2O \rightarrow 4Al(OH)_3$
Sodium Based	Sodium Sulphur (Na/S)	$2Na + xS \leftrightarrow Na_2S_x \quad , x \in [2.7,5]$
	Sodium Nickel Chloride ($Na/NiCl_2$)	$2Na + NiCl_2 \leftrightarrow Ni + 2NaCl$
Lithium Based	Lithium Ion (Li-Ion)	$Li_xC + Li_{1-x}M_yO_z \leftrightarrow C + LiM_yO_z$
	Lithium Ion Polymer (Li-Polymer)	$xLi + M_yO_z \leftrightarrow Li_xM_yO_z$

Alternative Energy Sources

- The possible alternatives to batteries as portable energy sources that are being investigated today for electric vehicles (EVs) and hybrid electric vehicles (HEVs) and other applications are fuel cells and flywheels
- Ultracapacitor technology has advanced tremendously in recent years, although it is unlikely to achieve specific energy levels high enough to serve as the sole energy source of a vehicle
- However, ultracapacitors in conjunction with a battery or fuel cell have the possibility of being excellent portable energy sources with sufficient specific energy and specific power for the next generation of vehicles.

Fuel Cells

fuel cell is an electrochemical device that produces electricity by means of a chemical reaction, much like a battery.

The major difference between batteries and fuel cells is that the latter can produce electricity as long as fuel is supplied, while batteries produce electricity from stored chemical energy and, hence, require frequent recharging.

The basic structure of a fuel cell consists of an anode and a cathode, similar to a battery. The fuel supplied to the cell is hydrogen and oxygen.

The flow of electrons from the anode to the cathode through the external circuit is what produces electricity. For the overall cell reaction to complete, oxygen or air must be passed over the cathode.

The cathode reaction takes place in two stages. First, the bond between the two oxygen atoms in the molecule breaks and then each ionized oxygen atom grabs two electrons coming from the anode through the external circuit to become negatively charged.

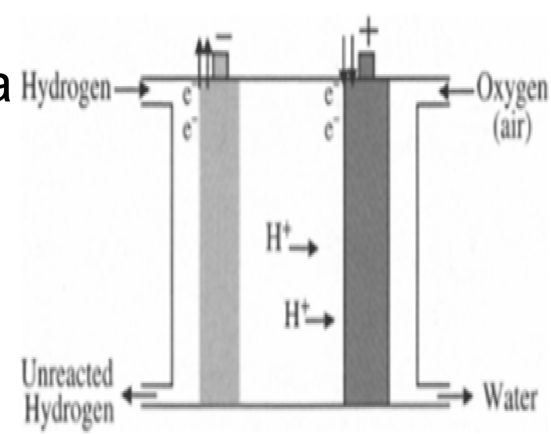
The negatively charged oxygen atoms are balanced by the positively charged hydrogen atoms at the cathode, and the combination produces H2O commonly known as water.

The chemical reaction taking place in a fuel cell is a

Anode: $H_2 \rightarrow 2H^+ + 2e^-$

Cathode: $2e^- + 2H^+ + \frac{1}{2}(O_2) \rightarrow H_2O$

Cell: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$



- There are several different types of fuel cells, each with strengths and weaknesses.
- Low operating temperature is desirable for vehicle applications, despite the fact that higher temperatures result in higher reaction rates.
- Rapid operation and co-generation capabilities are desirable for stationary applications.
- Cogeneration refers to the capability to utilize the waste heat of a fuel cell to generate electricity using conventional means.

fuel cell for the vehicular application

Disdvantages: size, cost, efficiency, and start-up transient times of fuel cells are yet to be at an acceptable stage for EV and HEV applications.(under research)

The complexity of the controller required for fuel cell operation is another aspect that needs further attention.

Although its viability has been well-proven in the space program, as well as in prototype vehicles, its immature status makes it a longer-term enabling technology for an EV and HEV.

Fuel Cell Variety	Fuel	Electrolyte	Operating Temperature	Efficiency	Applications
Phosphoric acid	H_2, reformate (LNG, methanol)	Phosphoric acid	~200°C	40–50%	Stationary (>250 kW)
Alkaline	H_2	Potassium hydroxide solution	~80°C	40–50%	Mobile
Proton exchange membrane	H_2, reformate (LNG, methanol)	Polymer ion exchange film	~80°C	40–50%	EV and HEV, industrial up to –80 kW
Direct methanol	Methanol, ethanol	Solid polymer	90–100°C	~30%	EV and HEVs, small portable devices (1 W to 70 kW)
Molten carbonate	H_2, CO (coal gas, LNG, methanol)	Carbonate	600–700°C	50–60%	Stationary (>250 kW)
Solid oxide	H_2, CO (coal gas, LNG, methanol)	Yttria-stabilized zirconia	~1000°C	50–65%	Stationary

Electrolytic capacitor

- Capacitors are devices that store energy by the separation of equal positive and negative electrostatic charges.
- The basic structure of a capacitor consists of two conductors, known as plates, separated by a dielectric, which is an insulator.
- The power densities of conventional capacitors are extremely high (~1012 W/m3), but the energy density is very low (~50 Wh/m3).
- These conventional capacitors are commonly known as “electrolytic capacitors.” They are widely used in electrical circuits as intermediate energy storage elements for time constants that are of a completely different domain and are of much smaller order compared to the energy storage devices that are to serve as the primary energy sources for EVs. The capacitors are described in terms of capacitance, which is directly proportional to the dielectric constant of the insulating material and inversely proportional to the space between the two conducting plates. The capacitance is measured by the ratio of the magnitude of the charge between either plate and the potential difference between them (C=q/V).

Supercapacitors/ultracapacitor

- Supercapacitors contain an electrolyte that enables the storage of electrostatic charge in the form of ions, in addition to conventional energy storage in electrostatic charges, like in an electrolytic capacitor.
- The internal functions in a supercapacitor do not involve electrochemical reaction.
- The electrodes in supercapacitors are made of porous carbon with high internal surface area to help absorb the ions and provide a much higher charge density than is possible in a conventional capacitor.
- The ions move much more slowly than electrons, enabling a much longer time constant for charging and discharging compared to electrolytic capacitors.
- Ultracapacitors are versions of electrolytic capacitors that use electrochemical systems to store energy in a polarized liquid layer at the interface between an ionically conducting electrolyte and an electrically conducting electrode.

Advantages:

On the other hand, supercapacitors and ultracapacitors with high specific power are suitable as an intermediate energy transfer device in conjunction with batteries or fuel cells in EVs and HEVs to provide sudden transient power demand, such as during acceleration and hill climbing.

Advantages &disadvantages in terms of ED&PD

- Supercapacitors and ultracapacitors are derivatives of conventional capacitor
- where energy density has been increased at the expense of power density to make the devices function more like a battery. Power density and energy density of supercapacitors and ultracapacitors are of the order of 106W/m3 and 104 Wh/m3 respectively.
- Energy density is much lower compared to those of batteries (~5 to 25×104 Wh/m3), but the discharge times are much faster (110 s compared to ~5×103 s of batteries), and the cycle life is much more (~105 compared to 100 to 1000 of batteries).

FLYWHEEL

- The flywheel is the kind of energy supply unit, that stores energy in mechanical form.
- Flywheels store kinetic energy within a rotating wheel-like rotor or disk made of composite materials.
- Flywheels can be used in HEVs with a standard IC engine as a power assist device.
- flywheels can be used to replace chemical batteries in EVs to serve as the primary energy source or could be used in conjunction with batteries.
- However, technological breakthroughs in increasing the specific energy of flywheels are necessary before they can be considered as the energy source for EVs and HEVs.
- Drawback: complex, large, and heavy. Safety is also a concern with flywheels
- Still research going on

Onboard energy storage

By using charging station:

Using energy storage for EV charging has some notable synergies with other benefits.

advantages:

Distributed storage for EV charging could be part of a localized strategy to integrate distributed photovoltaics and to provide very reliable electrical service in specific parts of the grid.

Charging at night when demand for electricity is low would smooth demand, thus reducing the utilities' overall cost-of-service.

Energy Storage Systems

Battery Charging Technologies

Charging schemes for a EV

- Normal charging
  - [1-Ph AC, 110 – 240 V, 13 – 20 A, 2 – 4 KW]
- Opportunity charging
  - [3-Ph AC, 110 – 240 V, 32 – 80 A, 8 – 20 KW]
- Fast charging
  - [DC, 200 – 450 V, 80 – 200 A, 36 – 90 KW]
- Battery swapping

Battery charging technologies

Four major charging schemes: based on level voltage, current, power level, and the time of charging.

Normal charging- single phase AC system, voltage -110 to 240 volts. Currents -13 Amps to 20 Amps, -2 to 4 KW(homes, garages, and residential car parking),

takes a longer time, typically 5 to 8 hours and it is done mostly in the night time

Since the current is less and also it is done in night time, it does not burden the power system

on the other hand it helps the power system for load leveling, since the other loads are very less

--not very popular among customers, wants quick charging

opportunity charging-- uses 3 phase AC , voltage of 110 to 240 volts current --32-80 Amps, power range of 8 to 20 KW

Charging can be done anywhere public charging stn/ public parking

Since its intermittent charging, does not put stress on power system

Fast charging -DC system ,voltage - 200 volts to 450 volts current- 80 to 200 Amps, power -36 to 90 KW

It is a fast charging algorithm and it charges the battery by direct DC voltage system charges the battery in 20 to 30 minutes and the battery reaches typically 80% of its full charge capacity in the 30 minutes

Needs heavy charging platform, it requires a dedicated charging stations and dedicated hardware and safety protections in place

Also since this is a heavy system, it puts burden on the power system and it has to be designed and installed in concentration with the utility

Battery swapping–

Not actual charging, just swapping the batteries at the charging station

Advantages:

Time-5 to 10

Discharged batteries taken by the charging stations & charged during the night time

Doesn’t put any stress on power system, rather it helps it

drawback :

Requires a very large space for the charging starting to mechanically swap the batteries

Requires standardization of the battery packs

Charging Algorithms:

- Improve the charging efficiency
- Reduce charging time
- Enhancing the battery life
- Protect the battery

Charging algorithms:

- Constant current charging (CC)
- Constant voltage charging (CV)
- Constant current Constant voltage charging (CCCV)
- Multistage charging (MSC)
- Pulse charging
- Trickle charging(TC)

Constant current charging (CC)

It charges the battery at constant current

It is a very simple algorithm (nickel cadmium and nickel metal hydride batteries)

Higher the amount of current used to charge the battery, the charging time will be correspondingly less. But this comes at a cost of charging efficiency and vive versa

Optimum current level is maintained such that the charging efficiency is optimum, together with not allowing the battery temperature to go up

So the end of this charging process is decided based on the voltage level.

Once the battery is charged to its full capacity, the battery voltage will start dropping rather than increasing, so that decides that this charging needs to be stopped

Charging algorithm requires

- Current sensor for controlling the current,
- Voltage sensor for stopping the charging, and
- Temperature sensor for thermal protection.

Constant voltage charging (CV)

- It is a constant voltage system based charging, but in this current is limited
- Has charging scheme, which tells the maximum amount of current that can be allowed to charge the battery
- Battery charges and it attains its full capacity
- Current taken by the battery becomes lesser and lesser and it becomes almost constant and very low magnitude current flows when battery reaches its full capacity
- So the constant small current will last for around three hours before the system can be stopped

Constant current Constant voltage charging (CCCV)

- This is a hybrid charging algorithm
- It has advantage of constant current and constant voltage charging both
- To charge the battery quickly, charging process at start will be CC.
- In this scheme, the charging starts in constant current mode and when the voltage or the charge level reaches a threshold, it moves to constant voltage charging.
- Under constant voltage charging, the current magnitude is relatively less and it will charge from 80% to the full capacity at very small current magnitude
- Charging scheme is used in lead acid batteries and lithium ion batteries.

Multistage charging scheme(MSC)

- Charging takes place in various stages
- This charging gives variable magnitude of current at different stages of charging
- It starts with high current magnitude and the magnitude of current decreases as the charge of the battery increases
- When the battery is reaching its full capacity, the requirement of current becomes less
- It's a kind of variable current magnitude, which is progressively decreasing from starting towards the end of charging
- popular in charigng lithium ion batteries.

Pulse charging/ Trickle charging

- Pulse charging is very similar to multistage charging
- It is done in pulses. It gives pulses of current in decreasing fashion.
- It starts with a high current pulse followed by the current pulse of lower magnitude
- Trickle charging is basically a charging done to keep the battery in charged condition. So once the battery is fully charged and if we left it unattended, it will discharge because of self charging and other losses
- This kind of charging enables keeping the battery in fully charged condition and supplying only the losses, which occur due to self discharge.

Unit 3:- HYBRID AND ELECTRIC DRIVETRAINS

Battery charging Technologies

Medium of charge Transfer:

- Conductive(wired)
- Wireless(WPT)

Conductive(wire):Wired power transfer or charge transfer is conductive in nature

ADVANTAGE:

It's very simple, low cost, and It has high efficiency

DISADVANTAGE:

very inconvenient

Need to carry the charging cables and

risk of electrical shock to the operator

Wireless(WPT):

Advantage:

Very convenient

operator is free from electrical shock

DISADVANTAGE:

High installation cost, because of the hardware involved

Chances of high power loss, which will decrease the charging efficiency

Different methods of implementing wireless power transfer

- Far-field strategies :
- Near-field strategies

Far-field strategies :

Uses high frequency and it can transfer high power at long distances

It is based on microwave or laser type of technology.

This technology is not suitable for EV, because it involves tracking strategies, antennas, and it's also prone to human health.

Near-field strategies:

CAPACITIVE

INDUCTIVE

CAPACITIVE:

Capacitive method uses electric field to transfer the charge to the battery

unaffected by metal barriers and it also does not emit any EMI problems

capacitive type of wireless power transfer is suitable for low power application and it is not suitable for a typical EV application

INDUCTIVE:

EMI is in magnetic based inductive systems

But this technology is very sensitive to air gap and the displacement of the charging plates

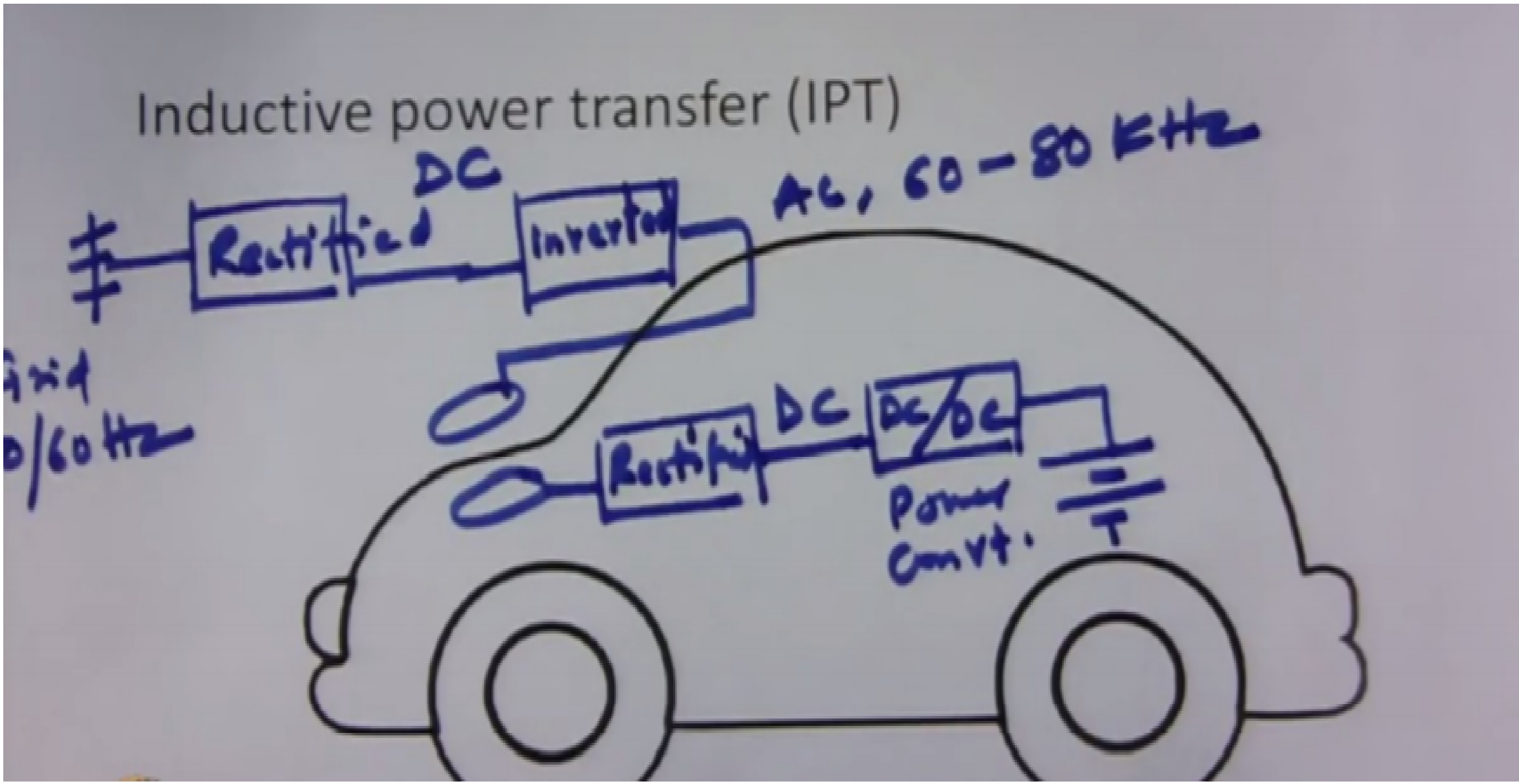
Iductive based mechanically coupled wireless power transfer promises a very good technology for wireless power transfer

It uses a phenomenon known as magnetic resonant coupling or MRC such that the high power can be transferred in the range 10s of KW over 10s of cm

Iinevitable, the inductive schemes may suffer EMI issues

It also suffers from energy loss due to leakage inductances.

Inductive Power Transfer



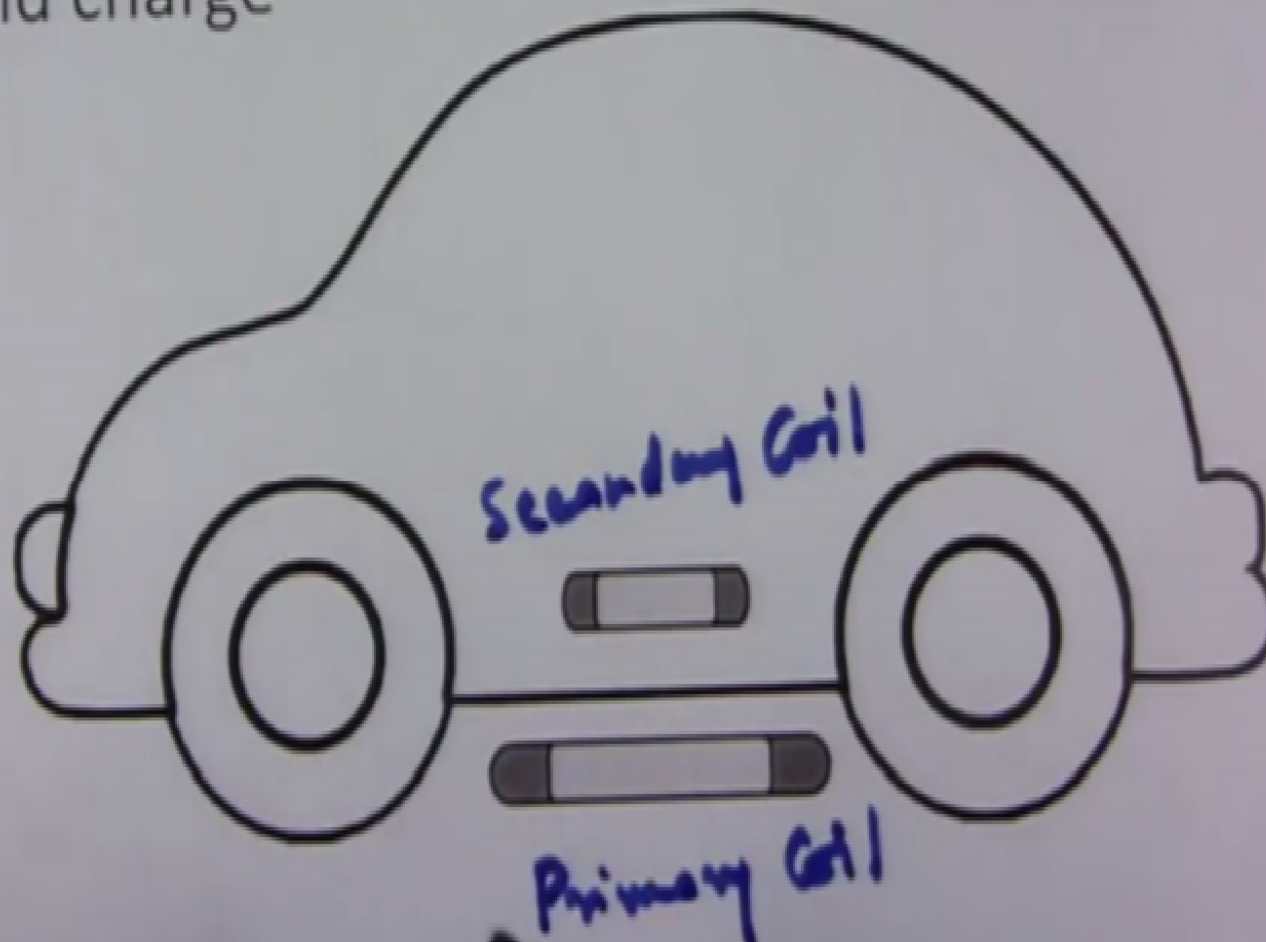
Scheme of inductive power transfer.

- It transfers energy through inductive coupling
- There will be two coils, one on the charging coupler and one inside the vehicle
- Power is taken from the grid(50 to 60 Hz), is rectified and converted to DC voltage, it is inverted using an inverter and AC voltage is generated at very high frequency in the range of 60 to 80 KHz.
- This high frequency enables a very small inductive coupler and the size of the coils can be reduced at this high frequency.
- Power will be transferred using inductive medium and it is available on the secondary side, which is again rectified and converted to regulated DC
- This DC voltage is used to charge the battery using DC-DC power converter

Inductive power transfer

- Park and charge

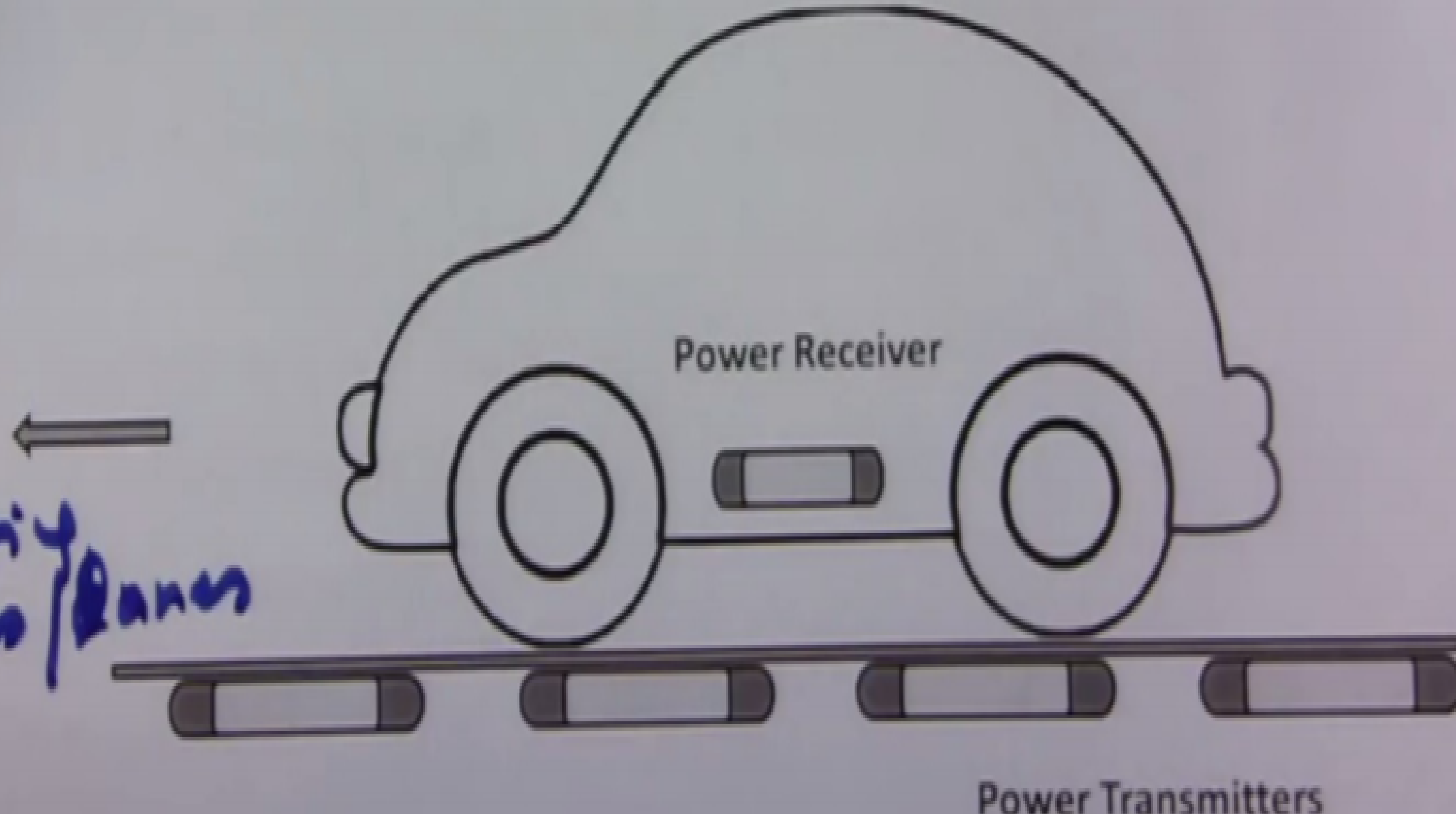
Magnetic Resonant Coupling (MRC)



Inductive power transfer

- Move and charge

charging zone / lanes



PARK & CHARGE

- Inductive coils are installed on the floor of the parking area
- Primary coil will be installed in the basement of the parking area and secondary coil will be installed on the chassis of the vehicle
- Whenever vehicle is parked, an automatic charging can be enabled.
- No inconvenience to the driver or the operator
- Charging scheme uses magnetic resonant coupling phenomenon, such that power will be transferred efficiently and during power transfer the non resonant object such as metal body or the driver is unaffected by it.
- Protection is kind of in-built in this kind of scheme.

MOVE & CHARGE

- To charge this vehicle when they are plying on the road
- Done at charging zones or lanes in some areas of the city, where lot of primary coils will be installed over half a km or 1 km
- when vehicle move on this kind of lanes the power will be transferred to the vehicle using inductive phenomenon

Advantages : vehicle can be charged

On the go

Battery size can be less

Anxiety of driving range will also be minimized

MOVE & CHARGE

IMPLEMENTATION REQUIREMENT:

- Charging scheme may observe different resonant frequencies because of the vertical distance and the horizontal distance.
- This primary and secondary or the transmitter receiver observes, when the vehicle is moving. Therefore, the power transmitters should be able to be configured dynamically such that the coupling can be maximum and the power transfer can be maximum.
- Secondly, when such a charging zone or lanes were developed, they should consider a uniformity in the magnetic field all around the road, such that the coupling can be same and charging can be done properly with high efficiency.
- Communication protocol has to be developed such that the vehicle that are meant to be charged are only charged and not all the vehicles.
- Since the battery energy storage capacity is limited, it is always a important aspect to manage the battery and energy associated with the battery.

Battery Management system (BMS) for EV and HEV

Measures voltage, current , temprature data in real time system and log it for the following:

- Cell balancing, Thermal management
- Protections: overvolatage, overcurrent & overheat
- State of charge(SOC)
- State of health (SOH)
- State of Power (SOP)

Unit 3:- HYBRID AND ELECTRIC DRIVETRAINS

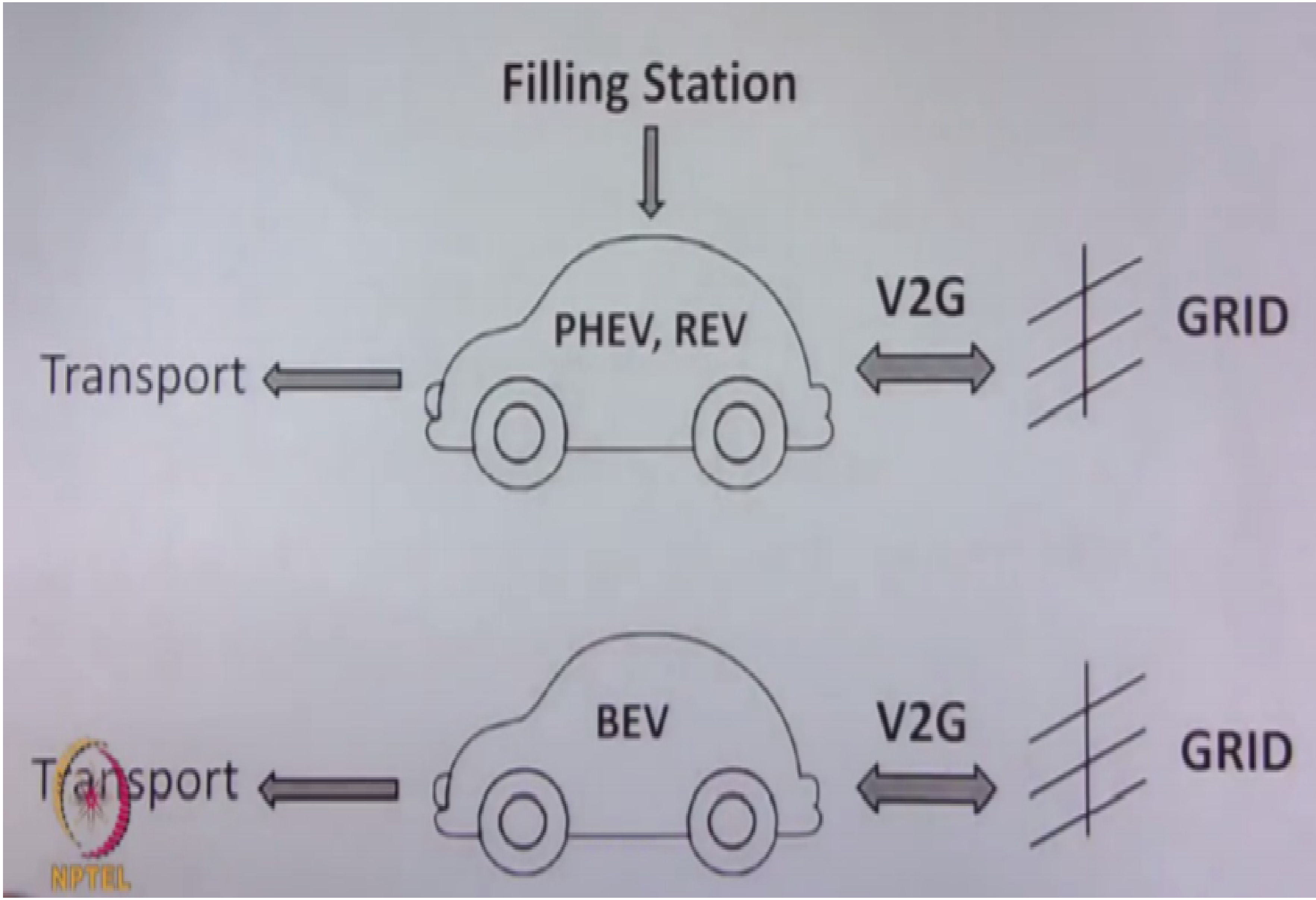
Syllabus…Unit 3 Focus On….

Lecture	Topics to be covered
L1	Basics about battery, Energy source used for EV’s & HEV’s, Ragone Plot,
L2	Battery Performance Characteristics- Battery Capacity, Open circuit terminal voltages, Charage and Discharge rates, SOC, SOD, DOD, Battery Energy Density, power density, Specific energy and Specific Power.
L3	Types of batteries. Comparison of batteries, Ultra capacitors and Ultra flywheels, fuel cells. On board energy sources.
L4	Charging schemes for EV’s, charging characteristics, different types of charging, CC, CV, CCCV, MSC, Pulse charging & Trickle charging.
L5	Conductive and wireless power transfer, Inductive Power Transfer, Battery Management system (BMS) for EV and HEV,
L6	Vehicle to grid configuration, EV energy systems and configuration
L7	HEV modes of operations starting the system, acceleration and deceleration of the system, normal driving, regenerative braking, the charging of the battery when the vehicle is in motion or when the vehicle is at rest.

Vehicle to grid technologies

- Comprises of:
- Grid-able Evs: EVs which can be connected to grid
- Utility or power system
- Information technology

Electric vehicles use batteries for energy storage systems, therefore because of the availability of batteries and if that EV is capable of connecting to grid, it is possible to use those batteries as power generators and it is possible to interchange energy between the battery and the grid or grid to the battery while charging. Therefore, this technology enables integration of energy flow and the information flow such that both the EV owners and the power grid or the power system gets benefited


Filling Station
PHEV, REV
Transport
V2G
GRID
BEV
Transport
V2G
GRID
NPTEL

grid-able EVs

- EVs which can be connected to grid are known as grid-able EVs
- Hybrid electric vehicle, PHEV and REV are grid-able, means they can be connected to grid for charging the battery
- They can be also charged using petrol or diesel from a filling station.
- BEV always charges the battery from grid, but it is also possible to connect these two systems such that they can enable the power flow from the vehicle to the grid. So this system requires the capability to transfer energy both from the grid to vehicle and from vehicle to grid.

V2G as a emerging new business model

- It can communicate with the grid

--- can control the energy flow from the battery to the grid

---can also control the charging rate of the batteries

- EV are unused for 95% of the Time
- Each EV can typically store/generate between 4 kWhr to 80 kWhr
- If EV in large scale then 20 to 40% penetration is there in the vehicle segment.
- On mass scale It can create its own autonomous power storage.
- May effect the power system dynamics and stability

Need of power aggregator: power aggregator has to take care of internal energy flow such that it minimizes the power demand and losses

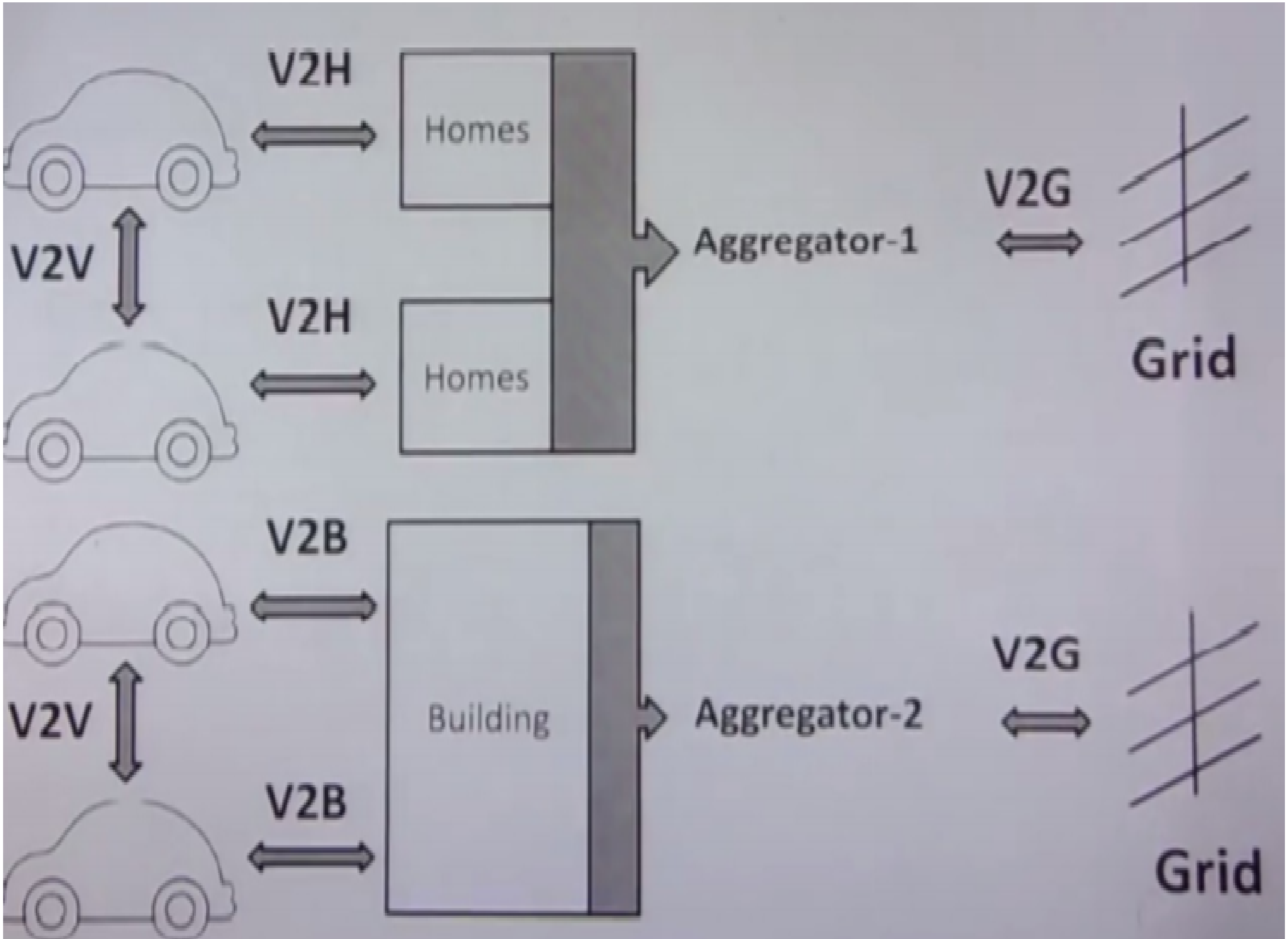
- Individual EVs V2G action is ineffective/insufficient
- Create a pool of Evs and communicate to the grid
- Performs energy arbitrage internally within the pool

--Enable V2V, V2B, V2H intragrid operators

--Minimizes power demand and losses

--Optimizes voltage deviations, Total Harmonic Distortion

--Estimate prices for maximum profit



V2H
Homes
V2H
Homes
V2V
Aggregator-1
V2G
Grid
V2B
V2V
Building
V2B
Aggregator-2
V2G
Grid

V2G applications in Power systems

- Co-ordinated charging and peak shaving
- Active regulation
- Spinning reserve
- Motor starting
- Reactive Regulation
- Renewable transients etc

Power convertor for V2G operation

- battery bank and 2 power converter
- source of energy 3-ph(connect a diode rectifier) for charging capability
- use of bidirectional power converter which can support the energy flow from battery to the grid
- DC link as electrolytic capacitors, so this can be used to support, reactive power support to the grid
- act as a shunt to the grid and it can enable in maintaining the THD of the grid and also support reactive power compensation required during voltage regulation and motor starting
- called basically grid side converter

EV energy systems and configuration

EV requires multidisciplinary technologies:

Electrical engineering: Electrical machines, power electronics, control systems, energy and battery management systems and charging

Mechanical and automobile engineering:

Gearing, differential, chassis, suspension, braking, steering etc

The knowledge of IC engine is required in a HEV or hybrid electric vehicle.

Chemical engineering :

knowledge of battery, fuel cell, liquid and gaseous fuels and its different kind of chemical features are required to be known

EV configuration

- Converted EV

Heavy wt, loss of flexibility

- Purpose Built

Energy flow via flexible wiring

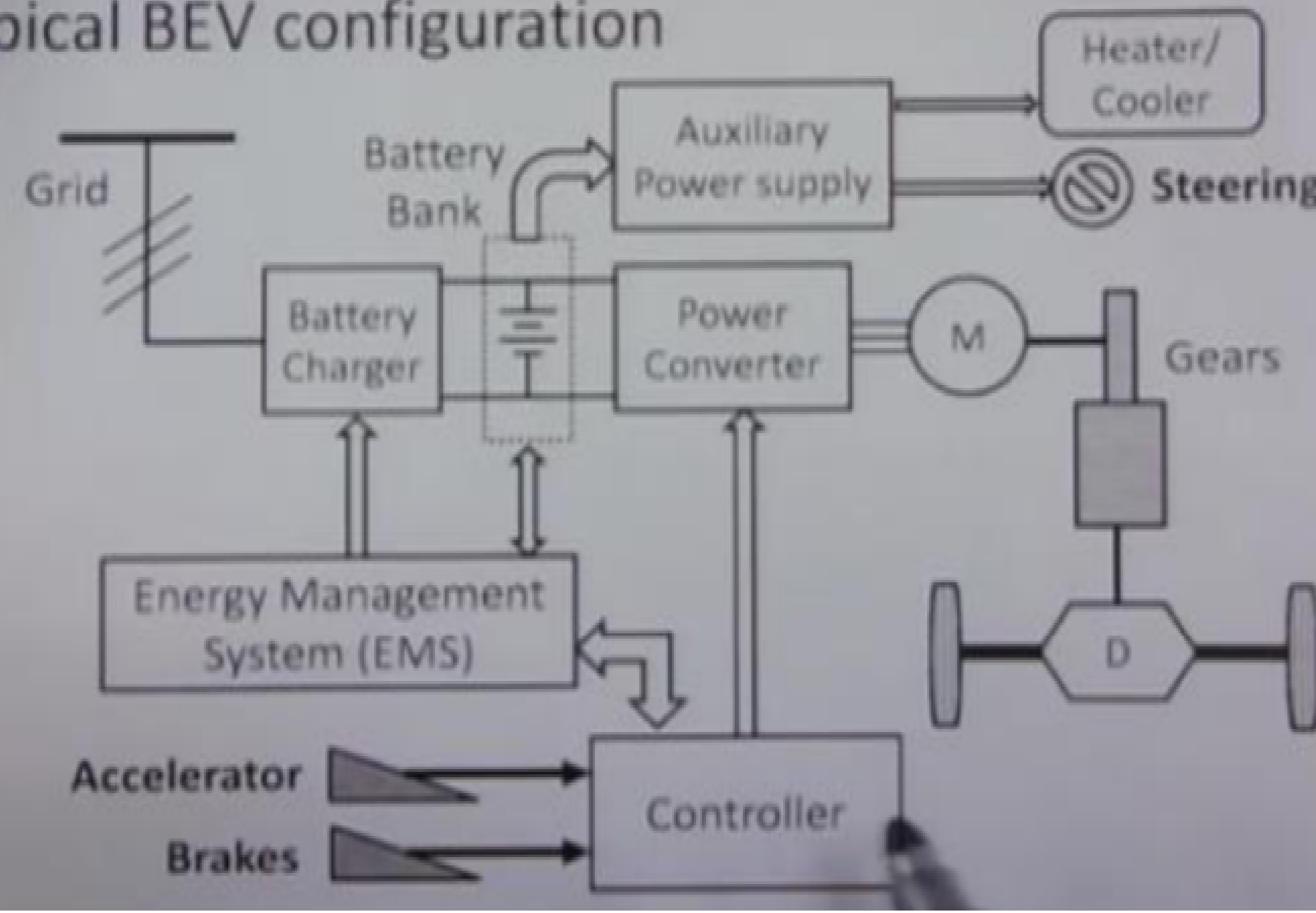
Propulsion (single/multiple motor)

Energy sources(hybrid, charging systems)

Components of a typical EV system

- Electrical propulsion system:controller, power converter or power electronics, motor, transmission gears, differential, wheels etc
- Energy source subsystem:Energy source, selection of energy source, design of chargers or the refilling systems, energy management system
- Auxiliary subsystem: power steering, cooling arrangement, heating arrangement, infotainment etc

Typical BEV configuration



Converted EV's-

- Use the technology of IC engine
- Longitudinal front engine, front wheel drives.
- Replaces the IC engine with a similar rated motor, and the rest of the mechanical assembly is same like it has clutch, it has a gear box which is a variable gear system and a differential
- Requirement of the motor is, it should work at full speed with capacity of delivering the full torque
- Variable speed and variable torque operation is done by the variable gear systems by means of clutch system

Advantage:

- SIMPLE, not need much expertise

Disadvantage:

- Heavy wt, loss of flexibility

Applications

- Three wheeler or a very smaller rated car with simple conventional motor.

VARIOUS CONFIGURATION OF EV

- Longitudinal wheel drive (same mechanical assembly)
- Longitudinal wheel drive(Fixed gear no clutch)
- Transverse wheel drive
- Transverse wheel drive (Fixed gear no clutch)
- Dual motor drive
- In-wheel motor drive
- Outer rotor motor drive

VARIOUS CONFIGURATION OF EV

- WITH BATTERY ENERGY STORAGE
- WITH HYBRID BATTERY
- WITH FUEL CELL AS ENERGY STORAGE
- WITH UC/FW AS ENERGY STORAGE
- BEV configuration : system voltage

BEV configuration : system voltage

- Motor Design is related to system voltage
- High voltage motors

1. Reduces cost/size of power convertor
2. Need large no of batteries in series
3. Reduction of interior and luggage space
4. Weight/cost of vehicle will increase
5. Performance will degrade

- System voltage is governed by battery weight
- High power motors adopt high voltages

Differentiation between single/multiple motor configurations

	Single motor	Multiple motor
Cost	LOW	HIGH
Size	LUMPED	DISTRIBUTED
Weight	LUMPED	DISTRIBUTED
Motor rating	HIGH	LOWER
Efficiency	LOWER	HIGH
Differential	MECHANICAL	ELECTRONIC
Controllability	LOW	HIGH
Reliability	HIGH	HIGH ONLY WITH FAULT TOLERANT CONTROL

Differentiation between Fixed/Variable Gear system

	Fixed gearing	Variable gearing
Power convertor rating	Higher	Lower
Motor rating	Higher	Lower
Efficiency	Higher	Lower
Reliability	Higher	Lower
Motor design	Customised/complex	Conventional Motors
weight/size	Lower/smaller	Higher/larger
Cost	Lower	Higher
System operation	simple	Complex

Differentiation within wheel drives

Inner rotor type	Outer rotor type
High speed rotor	Low speed
Smaller size	bigger
Light weight	heavier
Lower cost	More costly
Speed reduction planetary gear-set is adopted	Gear-less
	Simple

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HEV modes of operations

Starting

Acceleration/Deceleration

Normal driving

Regenerative braking

Battery Charging when the vehicle is in motion/Rest

Starting, Acceleration/Deceleration,Normal driving

For Series HEV configuration:

For starting the system and during normal driving and acceleration, the full system is active

Mechanical energy is transferred from IC engine to the motor via electrical generator together with the energy stored in the battery to the electrical motor

Whole system is active during this mode of operation

During light load on the transmission system:

Mechanical energy is transferred from the IC engine to the electrical motor, a part of it will be used to charge the battery

IC engine operate at maximum efficiency

During light load, part of energy is transferred to the battery for charging

Deceleration/Breaking

During deceleration –

- Regenerative energy is absorbed by battery during braking operation
- Energy is recovered from the wheels and the motor is operated as generator and mechanical energy is transferred to the battery via power converter mode
- Power converter has to be a bidirectional AC to DC converter if we are using a AC motor

Battery charging(standstill)

- It is possible to charge the battery when the vehicle is at rest
- by transferring the mechanical energy available from the IC engine to the battery, by operating, this motor as generator

Operation modes of a parallel HEV

IC engine is & electrical motor connected to the transmission

These drivetrains are connected individually to the transmission using different clutch

During startup or acceleration, both these systems will be on and maximum power can be transferrd for both startup and acceleration

During normal driving mode

IC engine based drivetrain is active and mechanical energy is transferred to the transmission

Electrical drivetrain is in off mode.

Deceleration/braking

- During deceleration
- Electrical drivetrain is only active and power is recovered from the wheels, and the recovered energy stored in the battery by operating the motor as generator
- Battery charging

When the vehicle is moving , Battery charging has to be done via transmission.

Mechanical energy required for the transmission has to come from IC engine based system, and a part of it will be transferred to the battery by operating the motor as generator.

Power flow happens through transmission in this case.

Operation modes of Complex series parallel HEV subsystems

Advantages of both series and parallel configuration

system is complex

Various kind of mode of operation is possible in these systems.

- Engine heavy series parallel
- HEV Electrical motor heavy series parallel HEV

IC engine heavy series parallel HEV

Startup:

Only electrical drivetrain

Acceleration:

Mechanical energy is transferred from the IC engine to the transmission in parallel to the electrical drivetrain based battery driven electrical motor type of propulsion

Generator is non-active in this mode

Normal driving:

IC engine based drivetrain is active, and the mechanical energy is transferred from the IC engine to the transmission, and the rest of the system is inactive. So the electrical drivetrain and the generator is turned off at that time

Deceleration/braking: Electrical drivetrain is active and the mechanical energy of the wheels is extracted by motor operating as generator and the battery is charged by the energy recovered from the wheels

Charging battery while driving:

While driving, the IC engine drives the transmission and a part of it can be used to charge the battery by operating the electrical generator

IC engine and the generator are connected by a complex planetary gear which enables connection and disconnection of electrical generator during driving operation

When vehicle is not moving or when it is at rest, it's possible to charge the battery by operating the generator while the mechanical propulsions are off.

Electric heavy type of series parallel HEV

Startup /light load conditions: Electric mode

Acceleration:

All three propulsion devices or mechanical devices are used to accelerate the system, so the system uses full torque capability of the system

Mechanical energy is transferred from IC engine to the transmission, and a part of it is transferred via generator to the motor

Third is from the battery to the motor

Normal driving:

IC engine is used to drive the transmission, a part of that mechanical energy is also transferred from generator to the motor for propulsion

In this mode of operation, the battery is not used

Deceleration/Braking :

Similar to IC engine heavy series parallel HEV

Power is recovered only from the electrical drivetrain.

Battery charging during motion/Standstill

Battery can be charged when the vehicle is in motion, when the mechanical power is transferred from the IC engine to the transmission

Battery charging at stand still is also similar to the IC engine heavy series parallel HEV and it is done by a charging the battery via electrical generator from mechanical power obtained from IC engine.

END