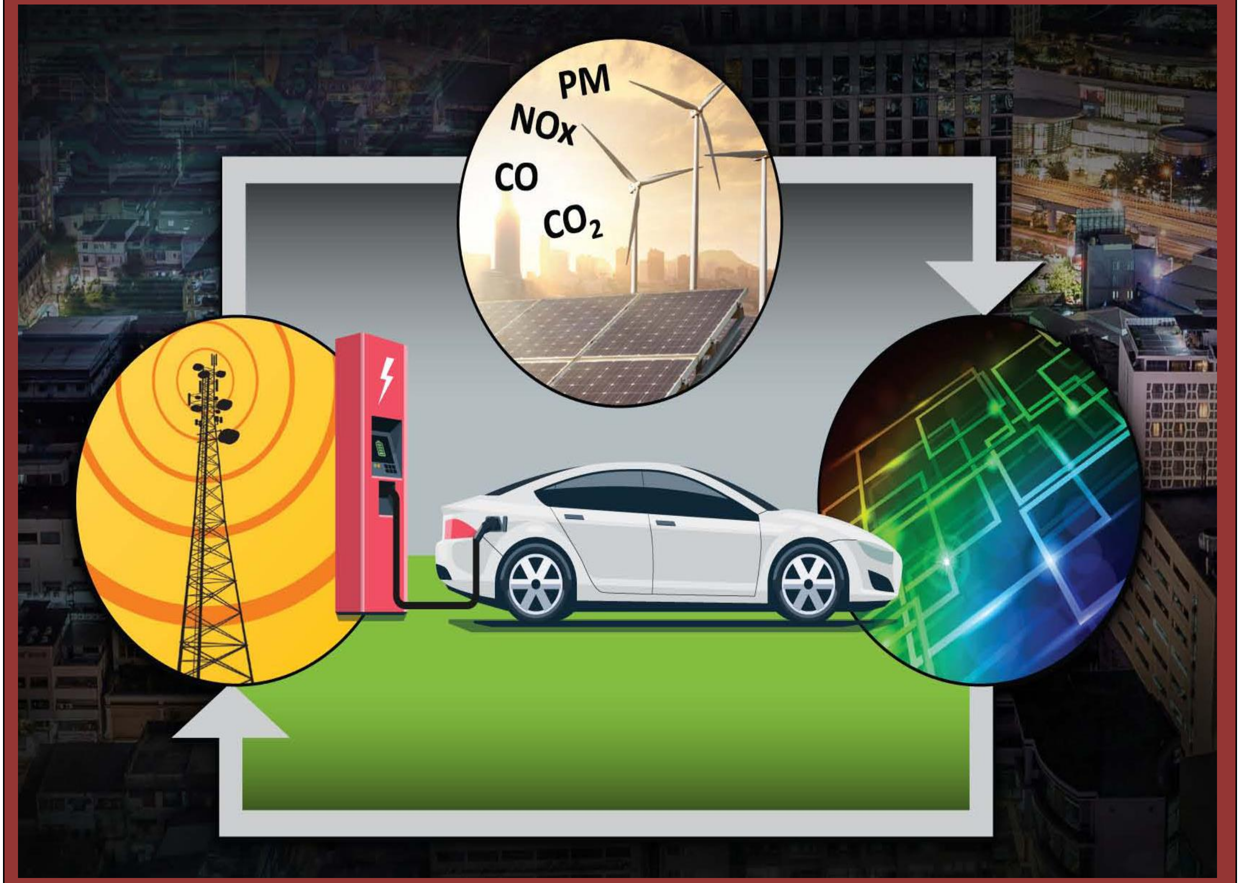
EEPE605 Electrical and Hybrid Vehicles



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① EEPE605 Electrical and Hybrid Vehicles.

Unit I :

Introduction : Conventional vehicles: Basics of vehicle performance, vehicle power source characterization, transmission characteristics Mathematical models to describe vehicle performance.

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Changes (Modernization) in Automobile Industry.

① New Vehicle Types :

- Previously Internal Combustion Engine (ICE). In recent decades hybrid electric technology has advanced significantly in automobile Industry.
- Hybrid is the ideal transitional phase between the traditional all-petroleum-fueled vehicle and the all-electric vehicles in future.
- Hybrid Electric Vehicle (HEV) is the one which is a Combination of an ICE and an electric motor.

- HEV can play a crucial role in resolving the environmental issues and the growth of energy insecurity.
- Hybrid Technology provides researchs in ensuring high standards in the electric motors, power electronics and batteries.
- HEV is a Complex system of mechanical & electrical components. Moreover they are generally nonlinear, exhibit fast Parameter variation & operate under uncertain and Changing Conditions. (Hot & cold Climatatic conditions)
- HEV system Control is also fundamentally a multivariable problem with many actuators, performance variables and sensors. This multi-variable designs may make control strategies less robust to parameter variations and uncertainities & make more difficult to calibrate.

- Apart from HEV, Plug-in Hybrid Electric Vehicles (PHEV), Fuel cell vehicles & electric bikes are becoming common. Eventhough Electric Vehicles (EV) have emerged, the above said PHEV, Fuel cell vehicle, HEV are not the replacement of ICE but provides new forms of mobility, managing energy consumptions and less pollution

② **Connectivity**

- Vehicle can communicate seamlessly with each other and with road infrastructure in place creating new opportunities for services for drivers Passengers & opens up new vistas of service delivery that can be monetized by Original Equipment Manufacturers (OEM)

③ Algorithmic development.

- Smart mobility can be achieved by Proper adoption of networking.
- With the association of large scale distributed control and optimization (for heavy lifting requirements) has been implemented for mathematical analysis.
- Very large scale distributed solutions can be implemented over graphs with time varying connectivity properties without the need of inter vehicle communication & done only from a central coordinator.

④ Demographic Changes.

- Younger generations are far away from traditional ownership vehicle models. & trend towards on-demand model. This creates new opportunities for OEM & creating the need for new financial models.

⑤ By Products of ICE & aggregation

ICE have 3 impacts

- Global warming
- By products harmful to humans (ozone, Benzene, nitrate oxide, Carbon monoxide)
- air qualities in cities.

⑥ Platform monetization

- Companies like Apple have paved way for usage of simple computing device in a more general delivery platform |||ly in Automobile Industries vehicle physical size, providing auxillary services to drivers & passengers.

⑦ Partial & full autonomy:

- The penultimate driving force in transportation is march towards autonomous driving. These depends on the OEMs.

⑧ Sustainability & Constrained resources.

- This is not only fuel availability based but also the spares availability

⑨ Regulation :

- Adopting changes in transport regulation
- Generally regulation is driven by

Safety

Greenhouse gases

Congestion

air quality

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Internal Combustion Engine (ICE)'s Environmental Impacts.

- ICE vehicles causes serious problems for the environment and human life.
- Airpollution, gas emission causing global warming, rapid depletion of the petrolium resourse are now new problems.

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- ## Air Pollution

- Most of the vehicles rely on combution of hydro carbon fuels to derive the power required for the propulsion.
- Hydro Carbon (HC) (or) Volatile Organic Compounds (VOC) is a chemical compound with molecule made up of carbon & hydrogen atoms.
- Combution of HC yields only carbon-di-oxide & water which doesnot harm the environment (Plant digests CO_2 by photo synthesis) & Animals donot suffer from breathing CO_2 unless oxygen is absent in air.
- But ICE are not ideal besides CO_2 and water it produces Nitrogen Oxides (NO_x), Carbon Monaxides (CO) and unburned Hydro carbons all are toxic to human health.

Nitrogen Oxides (NO_x)

- Results from the reaction between nitrogen in the air and oxygen.
- Temperature is by far the important parameter for NO_x formation. Nitric oxide (NO), small amount of NO_2, and traces of Nitrous Acid (N_2O) is also present in (NO_x).
- NO reacts with oxygen to form NO_2 & later decomposes to NO due to Sun's Ultra Violet radiation & highly reactive. Oxygen atom attack the membranes of the living cells.
- N_2O is partly responsible for Smog (its brownish colour makes visible)
- with atmospheric water forms nitric acid (HNO_3) which dilutes in rain (which is referred as "acid rain". (This degrades historical monuments made of marbles & destructs forests.

② Carbon Monoxide (CO)

- Results from incomplete Combustion of hydrocarbons due to lack of Oxygen which is poison to human & animals.
- Once CO reaches blood cells, it fixes to the hemoglobin in place of Oxygen which reduces the physical & mental abilities.
- Dizziness is the first symptoms of CO poisoning results to death.

· Unburned Hydrocarbon:

- Some Hydrocarbon (HC) may be direct Poisons. These are also referred as Carcinogenic Chemicals. (like Particulates, benzene etc)
- HC is responsible for smog.
- The Sun's Ultraviolet radiation interacts with HC & NO in the atmosphere

to form ozone & other products

- Ozone is a molecule formed of three oxygen atoms, it is colourless harmful poison.

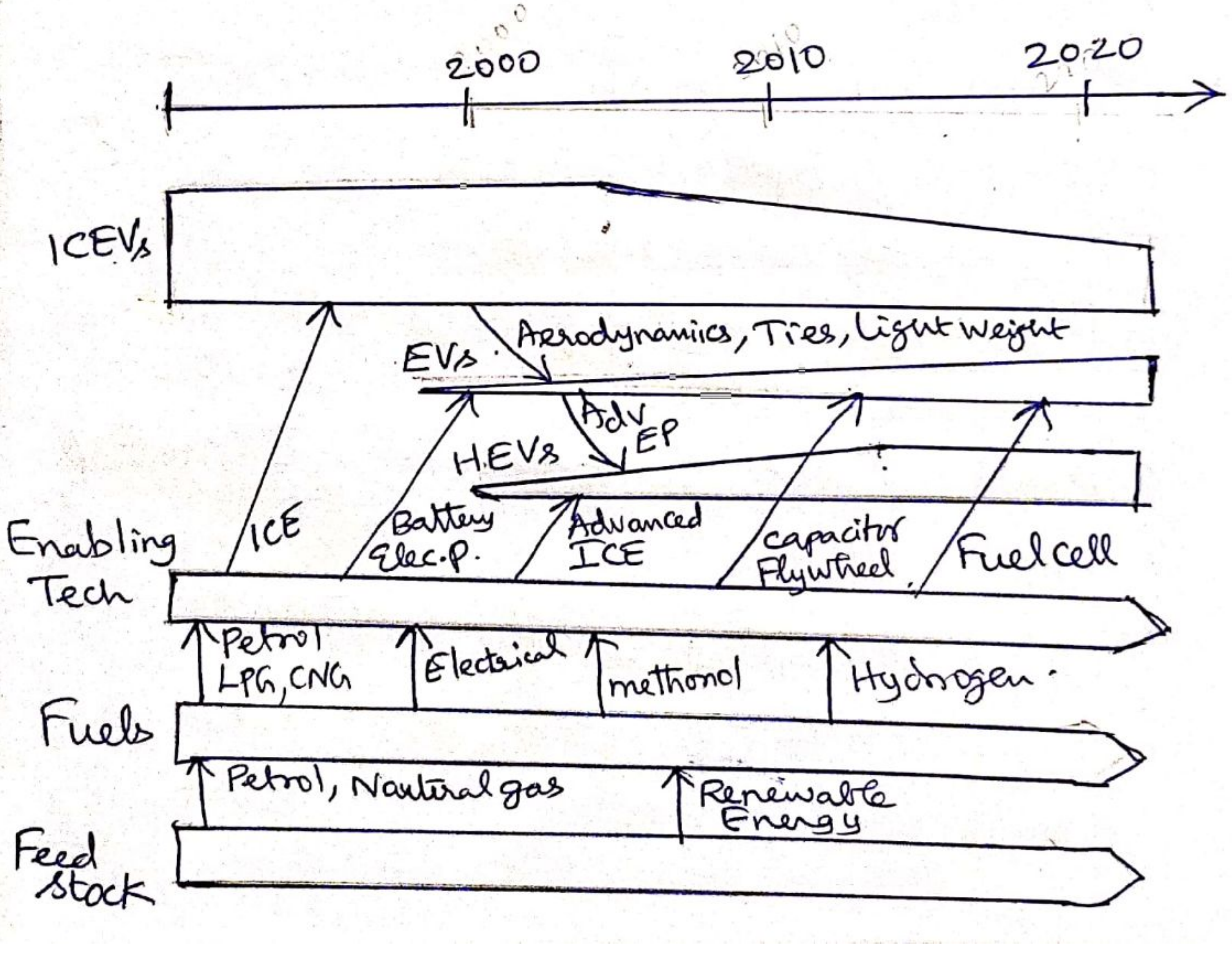
- Other pollutants:

- Major impurity is Sulfur & is mostly found in diesel, jet fuel and also in gasoline & natural gas.
- Combution of sulfur with sulfur oxides (SO_x) and majority is SO_2.
- SO_2 on contact with air forms sulfur trioxide when reacts with water forms sulfuric acid causing acid rain.
- SO_x eventhough orginates from transports but largely from coal power plants & steel factories, volcanoes etc.

- Petrol Companies add lead (Tetraethyl lead) was used to improve the knock resistance of gasoline & gives better engine performance but releases lead which causes neurological disease called "<u>Saturnism</u>".

Fig. Development trends of EVs and HEVs.

note
EP - Electric Propulsion



Modern EV should include State of Art Technologies from automobile, EEE, Chemical engineering, should adopt unique designs/suitable special manufacturing/optimal energy utiligation suitable for EV.

The following to be Considered for EV design.

- Design philosophy.
- Technical Specifications
- Market environment.
- Infrastructure required including the battery recycling.
- Overall system configuration, EV, HEV, Fuelcell EV
- Chassis & body of the Vehicle.
- Energy source - generation or storage, single or hybrid.

- Propulsion System : Motor, Converter (or) transmission type.
  - Single or multiple motors, gearless / geared, ICE system for HEV.
- Specification of Electric Propulsion.
  - Power, Torque, Speed
  - Energy Storage (Capacity, Voltage Current)
- Adopting Intelligent Energy Management System
- EV Subsystem's performance to View cost, performance + Safety.
- Optimizing efficiency of the vehicle on selected driving pattern & Operating condition.
- Optimizing overall system using Computer Simulation.

Body design of EV

There are two basic approaches

Conversion	Purpose built (groundup design)
• Engine & associated equipments of an existing ICEV replaced by electric motor & assories.	• Allows to have flexibility to coordinate & integrate Various EV subsystems to work more efficiently.
• Existing chasis can be utilized (suffers from greater Curb* weight higher Centre of gravity & unbalanced weight distribution.	• overall performance like range, gradebility acceleration & top speed can be improved
	• Consistant weight saving design.
	• Low drag Coefficient body design.
	• Low rolling resistance

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* To reduce Curb weight

- Light weight materials like Aluminium & Composite materials for body & Chassis be used.

- Low drag Coefficient body design can effectively reduce the vehicle aerodynamic resistance in highways or cruising (with tapered front & rear ends & adopting under cover & flat under floor design etc)
- Low rolling resistance tyres:
  - These are particularly effective in reducing the rolling resistance with the use of newly blended tyre polymer together with an increase in tyre pressure.

Electric Propulsion:

- Responsible for converting electrical to mechanical energy overcoming aerodynamic drag, rolling resistance drag and kinetic resistance.
- As the Torque-Speed characteristic of an Engine covers only a narrow range, the vehicle has to use up

gear changing mechanism.

- Modern drive : high torque low speed & constant power - high speed regions can be achieved through electronic control.
- Electric propulsion system consists of motor drive, transmission devices & wheels

motor drive ↓ Core of EV

transmission devices ↓ (sometimes optional)

motor drive → Consists of electric motor, Power converter electronic controller.

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③ Major requirements of EV motor drive.

- High Instant power & high powerdensity
- High Torque at low speeds for starting & Climbing ; & high speed at low torque for cruising.
- Fast Torque response.
- Very wide speed range including Constant torque & Constant power regions.
- High effeciency over wide speed & Torque ranges & also for regenerative braking.
- High reliability & robustness for Various vehicle operating Conditions
- Reliable cost.
- Several Kinds of motor drives are available for EVs.

- DC Motor drives traditionally used due to high torque at low speeds & easy to Control. (but commutator, brushes requires periodic maintance)
- But nowadays machines having high efficiency, high power density efficient regenerative braking, robust reliable & maintence free such as Vector controlled Induction Motor drives even though having low efficiency at light-load ranges.
- Permanent Magnet brushless motor Posses highest efficiency & power density over others but suffers from the difficulty in flux weakening Control for Constant-power high speed region.
- PM hybrid Motor a special type of PM brushless motor is used which has an auxilary dc field

winding is so incorporated so that the resultant flux of PM & fieldflux By adjusting the field excitation the airgap flux can be varied flexibly resulting to optimal efficiency over wide range of speed.

- Switched Reluctance Motor (SR) offers a promising features as their simplicity and reliability in both motor & Power converter configurations, wide speed range, limp-home capability (limp mode is a security feature which activates when the engine or transmission control unit picks up a fault. When fault is detected, limp mode will cause the less important parts of the car like airconditioning, to switch off & the speed of the car will be reduced) & efficient regenerative braking (suffers from torque ripples & acoustic noise problems)

For Transmission Devices

- Conventional gearing can no longer satisfy the needs of EVs. No planetary gear has been accepted as transmi devices.

note Planetary Gears are used as Speed reducers. They are used to slow down motors and increase the torque. Torque is the working power of the machine. This gear boxes where the input and output both have the same Centre of rotation.

- This planetary gearhead takes a high speed, low torque input from electric motor, then increases torque & reduces speed at the output by by the gearhead ratio.

Energy Sources :

- The main concern in commercializing EVs are its high initial cost & short driving range. These are due to the energy source available in EV.
- The Energy Sources developed should have.
    - High Specific energy & energy density
    - High Specific power & Power density
    - Fast & deep charging Capabilities
    - Long cycle & service lives.
    - low self discharging rate & high charging efficiency.
    - Safety & Cost effectiveness, maintance free.
    - Environmental friendly & recyclable.

Note

Specific Energy	Specific Power.
• Specific Energy (SE) or massic energy is the energy content per unit mass. • Sometimes it is called as gravimetric energy density (or) just energy density. (eventhough energy density refers to energy per unit volume) • The gravimetric energy storage density of a battery, expressed in watt-hours per kilogram (Wh/Kg)	• Specific Power is the power per unit mass. • This is the power-to-weight ratio is a measure of performance of an engine in a Vehicle or in a power plant. • Power generated by the engine divided by the mass. • Specific power Consumption (Kcal/Tonne) = Electrical Energy Consumption (KWh/Tonne) × Heat rate (KCal/KWh) • Specific Power (or) gravimetic Power density indicates loading capability.

Selection of Battery lies on
- Specific Energy
- Specific Power.
- Cost.

	Adv	Disadv
Lead acid Battery	Low cost High Specific Power	Short cycle life low Specific energy.
Nickel metal hydride battery	Relatively high Specific energy	High cost.

Lithium-ion
Lithium-polimer

Ultra capacitors.
Ultra high speed fly wheel
Fuel cell

Good.

Multiple Energy Sources (called as hybridization of energy sources) compromises Specific energy & Specific power.

ex Petrol high Sp. energy.
battery high Sp. Power.

Energy Management

- Compared with ICEVs, EVs offer relatively short driving range. So to maximize the stored energy Intelligent Energy Management Systems (EMS) is to be adopted using temperature sensors, discharging current, voltage of electric motor, vehicle speed & acceleration & also climate & environment.

Functions to be carriedout by EMS.

- To optimize the system energy flow.
- To indicate residual driving range by predicting the remaining energy availability
- Suggest more efficient driving behaviour
- To direct regenerative energy from braking to receptive energy sources like batteries
- To modulate temperature control in response to external climate
- To adjust lighting brightness in response to environment.
- To diagnose any incorrect operation or defective component of the energy source
- Battery operation statistics to be accounted & adopt suitable battery charging algorithm

- EMS coupled to Navigation system efficient planning can be ensured.

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Ⓐ Vehicle fundamentals

The performance of the vehicle can be adjudged based on Speed, gradeability, acceleration, fuel consumption & braking.

General description of vehicle movement

Figure shows the force acting on a vehicle moving up a grade.

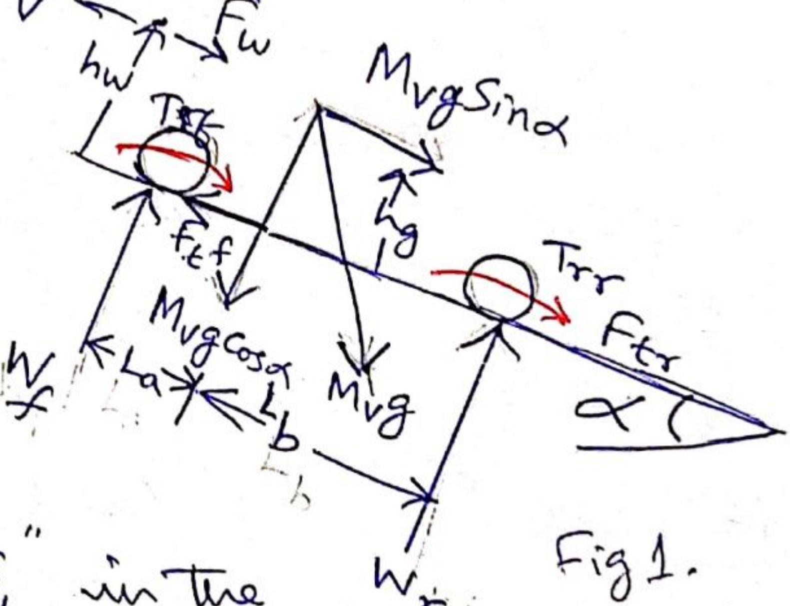


Fig 1.

Let Tractive Effort "F_t" in the contact area between tyres of the driven wheels & road surface propels the vehicle move forward.

- While the vehicle is moving the tyre resistance objects movement.
- Tyre resistance includes rolling resistance, aerodynamic drag & uphill resistance.

According to Newton's second law, vehicle acceleration

$$\frac{dV}{dt} = \frac{\Sigma F_t - \Sigma F_{tr}}{\delta M_v} \longrightarrow ①$$

where $V \rightarrow$ vehicle speed ; M_v Total mass of the vehicle

$\Sigma F_t \rightarrow$ total tractive effort of the vehicle ; $\Sigma F_{tr} \rightarrow$ Total resistance

$\delta \rightarrow$ mass factor which is an effect of rotating components in the power train.

From eqn ① Speed & acceleration depends on tractive effort, resistance & vehicle mass.

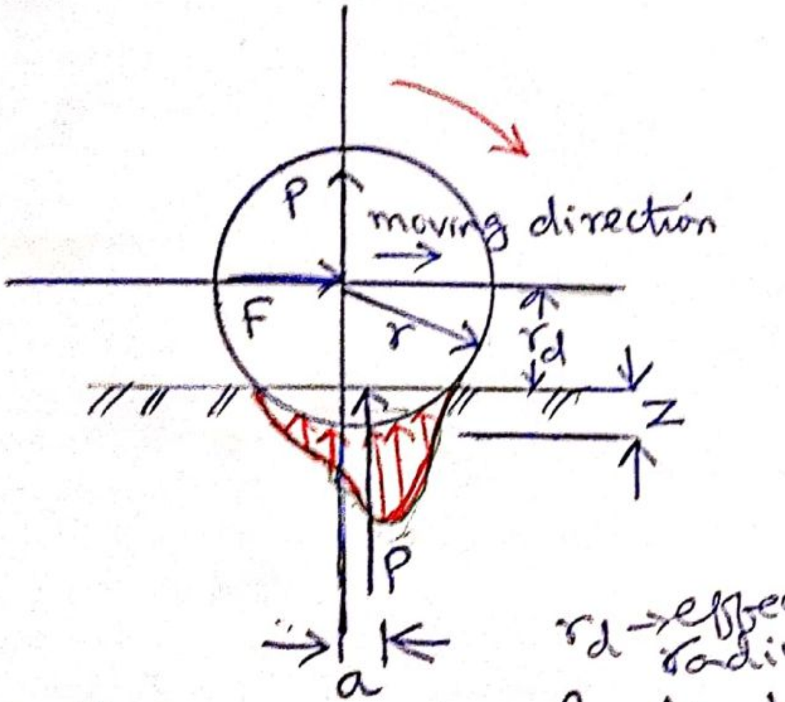
Vehicle Resistances:

- Opposing vehicle movement includes rolling resistance of the tyres, rolling resistance Torques T_{rf}, T_{rr}, aerodynam-ic drag (F_u) & grading resistances $(M_v g \sin\alpha)$.

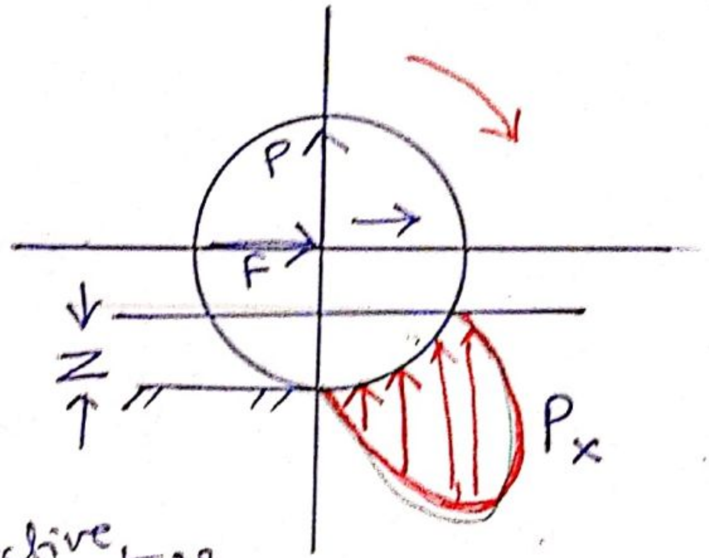
① Rolling Resistance:

- This rolling resistance of tyres on hard surface is primarily caused by hysterisis in the tyre material which is due to the deflection of the carcass as tyre rolls.

- The hysterisis causes an asymmetric distribution of ground reaction forces.



a) Pressure in the leading half of the contact area is larger than that of the trailing half.
This results in forwardly shifted ground reaction force, with normal load acting on the wheel center, creates a moment, that opposes the rolling of the wheel.



b) on soft surfaces rolling resistan caused by deformation of the ground surfaces that shifts to leading half

The moment produced by the forward shift of the resultant ground reaction force is called rolling resistant moment $T_r = Pa \longrightarrow$ ②
where P→ normal load acting on the Centre of the wheel

To keep the wheel rolling the force "f" acting on the Centre of the wheels is required to balance this rolling resistan moment

$$F = \frac{T_r}{r_d} = \frac{Pa}{r_d} = Pf_r \longrightarrow ③$$

where $f_r = a/r_d$ = Rolling Resistance Coefficient

When a Vehicle is operated on a slope road normal P is replaced by P Cos α

Resultant force $(F_r) = F = Pf_r \cos\alpha \longrightarrow ④$

where α → road angle.

The rolling resistance coeff f_r is a function of

- Tyre material
- Tyre structure
- Tyre Temperature

Any tyre life 3 years.

Tyre 3 types H tyre → Highway Tyre
A tyre → Altenate Tyre
Run flat → Higher end vehicles like Benz

Tyre Pressure
$|||^r$ to human BP. Tyre indication (manufacturing) week, year.

- Tyre inflation pressure
- Road roughness
- Road material
- Presence (or) absence of liquids on the road.

Low resistance coeff. less than 0.01

- Many empirical formulae have been proposed to calculate rolling resistance (for Passanger Car on concrete road)

$$f_r = f_o + f_r \left(\frac{V}{100} \right)^{2.5}$$

V → vehicle speed in Km/h

f_o, f_r → depends on inflation pressure of tyre.

Rolling Resistance Coefficient :- (f_r)

Condition	f_r
Concrete or asphalt	0.013
Rolled graval	0.02
Tar macadam	0.025
unpaved road	0.05
Field	0.1 – 0.35
wheels on rail	0.001 – 0.002

- It is sufficient to consider the rolling resi coeff as a linear function of speed

For Passanger Car on Concrete road

$$f_r = 0.01\left(1 + \frac{V}{100}\right) \longrightarrow ⑤$$

The eqn predicts for f_r for speeds upto 128Km/h.

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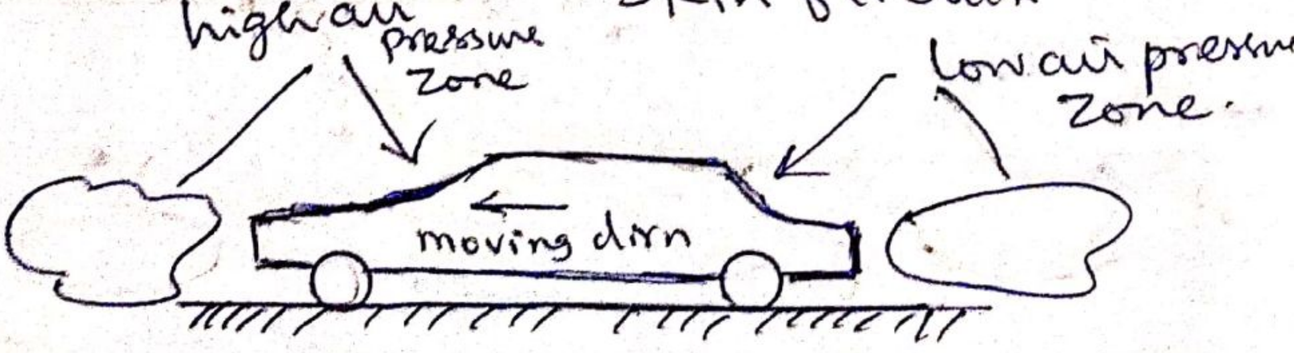
Aero dynamic Drag (AD):

- When a vehicle moves at a particular speed the air makes the Vehicle to encounter a force resisting its motion. This is called Aerodynamic Drag (AD)
- AD results from
  - Shape drag.
  - Skin friction



- This is a function of vehicle speed vehicle front area, Vehicle shape & air density.

#Shape drag :

- The forward motion of the vehicle pushes the air infront of it. As the air cannot move instantaneously of way its pressure increases.
- Moreover the air behind the vehicle cannot instantaneously fill the space left by the forward motion of the vehicle creating low air pressure zone. So 2 zones of air pressure have been created.
- The forward & backward pressure results
  (high pressure) (low pressure)
  the force on the vehicle as shap drag.

Skin Friction :

- Air close to the skin of the vehicle moves almost at the speed of the vehicle, while air far from the vehicle remains still.
- Air molecules move in between at a wide range of speeds.

- The difference in speed between the two air molecules produces a friction that results in the second component of aerodynamic drag.

$$F_w = \frac{1}{2}\rho A_f C_D (V+V_w)^2 \longrightarrow \textcircled{6}$$

ρ → air density

A_f → vehicle front area

C_D → aerodynamic drag coeff

V → vehicle speed

V_w → Component of wind speed on vehicle moving direction

+ when component is opposite to vehicle direction

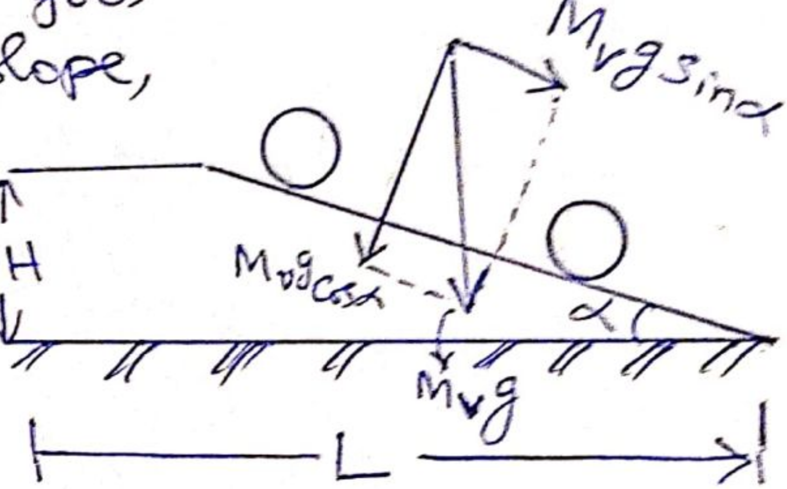
− ve when same direction.

Table: Aerodynamic drag coeff.

Vehicle Type	C_D
open type Van	0·5−0·7 0·5−0·7
Ponton body	0·4−0·55
Wedge shaped Head lamp & bumpers integrated into the body	0·3−0·4
Trucks, Road Trains	0·8−1·5
Motor cycle Buses	0·6−0·7

⑤ Grading Resistance:

- When a vehicle goes up or down in a slope, its weight produces a component which is always, directed to downward direction.



- This component either opposes the forward motion (grade climbing) or helps the forward motion (grade descending)
- Grading force (uphill operation) is usually called grading resistance.

$$F_g = M_v g \sin\alpha.$$

When the road angle (α) is small, α is replaced by grade value then the grade is defined as $i = \frac{H}{L} = \tan\alpha$
$\simeq \sin\alpha$.

- The tyre rolling resistance & grading resistance together is called <u>road resistance</u> which is expressed as

$$F_{rd} = F_f + F_g = M_v g (f \cos\alpha + \sin\alpha)$$

when α is small ; the road resistance

$$F_{rd} = F_f + F_g = M_v g (f_r + i)$$

Dynamic Equation :

- The major external forces acting a two axle vehicle shown above have rolling resistance of front & rear tyre in turn consitutes rolling resistance moment (T_{rf} and T_{TT}), aerodynamic drag (F_w), grading resistance (F_g) & tractive effort of the front & rear tyres (F_{tf} & F_{tr})

Note $F_{tf} = 0$ (for rear wheel driven vehicle)

$F_{tr} = 0$ (for front wheel driven vehicles)

The dynamic equation of vehicle motion is given by

$$M_v \frac{dV}{dt} = \underbrace{(F_{tf} + F_{tr})}_{\text{Total tractive effort}} - (\underbrace{F_{rf} + F_{rr} + F_w + F_g}_{\text{resistances}})$$

To predict the maximum tractive effort that the tyre ground contact can support, the normal loads on front & rear axies have to be determined.

Nominal load acting on the front axle (W_f)

$$= \frac{M_v g L_b \cos\alpha - (T_{rf} + T_{rr} + F_w h_w + M_v g h_g \sin\alpha + M_v h_g \frac{dv}{dt}}{L}$$

Nominal load acting on rear axle (W_r)

$$= \frac{M_v g L_a \cos\alpha - (T_{rf} + T_{rr} + R_w h_w + M_v h_g \sin\alpha + M_v h_g \frac{dv}{dt}}{L}$$

$\rightarrow$ ⑧ & ⑨

For passenger Cars:

Height of Center of application of aerodyn-amic resistance (h_w) is assumed to be near the height of Center of gravity of the Vehicle h_g.

Eqn ⑧ & ⑨ simplified as.

$$W_f = \frac{L_b}{L} M_v g \cos\alpha - \frac{h_g}{L}\left[F_w + F_g + M_v g f_r \frac{r_d}{h_g}\cos\alpha + M_v \frac{dv}{dt}\right]$$

$\rightarrow$ ⑩

$$W_r = \frac{L_a}{L} M_v g \cos\alpha + \frac{h_g}{L}\left[F_w + F_g + M_v g f_r \frac{r_d}{h_g}\cos\alpha + M_v \frac{dv}{dt}\right] \longrightarrow ⑪$$

Refering equns ④ & ⑦;

$$W_f = \underbrace{\frac{L_b}{L} M_v g \cos\alpha}_{\text{Static Component of load}} - \underbrace{\frac{h_g}{L}\left[F_t - F_r\left(1 - \frac{r_d}{h_g}\right)\right]}_{\text{Dynamic Component of load.}}$$

$$W_r = \frac{L_a}{L} M_v g \cos\alpha + \frac{h_g}{L}\left[F_t - F_r\left(1 - \frac{r_d}{h_g}\right)\right] \longrightarrow ⑫ \ \& \ ⑬$$

Where $F_t = F_{tf} + F_{tr}$

F_t ↙ Total Tractive effort of the vehicle

$F_r \rightarrow$ Coeff of rolling resistance (or) Total rolling resistance of vehicle.

The maximum tractive effort that the tyre-ground contact can support (any small amount over this maximum tractive effort will cause the tyre to spin on the ground) is usually expressed as

Normal load (W_f) × Road adhersion Coefficient (μ)

∴ For Front wheel driven vehicle

$$F_{t_{max}} = \mu W_f = \mu\left[\frac{L_b}{L} M_v g \cos\alpha - \frac{h_g}{L}\left(F_{t_{max}} - f_r\left(1-\frac{r_d}{h_g}\right)\right)\right] \rightarrow ⑭$$

$$= \frac{\mu M_v g \cos\alpha \left[L_b + f_r(h_g - r_d)\right]/L}{1 + \mu h_g/L} \longrightarrow ⑮$$

For rear wheel driven vehicle

$$F_{t_{max}} = \mu W_r = \mu\left[\frac{L_a}{L} M_v g \cos\alpha - \frac{h_g}{L}\left(F_{t_{max}} - f_r\left(1-\frac{r_d}{h_g}\right)\right)\right] \longrightarrow ⑯$$

$$= \frac{\mu M_v g \cos\alpha \left[L_a + f_r(h_g - r_d)\right]/L}{1 + \mu h_g/L} \longrightarrow ⑰$$

Note

The maximum tractive effort should not exceed eqn ⑮ or eqn ⑰ that are limitted by tyre ground cohesion, otherwise the driven wheels will spin on ground leading to vehicle instalility.

Tyre-ground adhesion & Maximum Tractive effort.

- When the tractive effort of a vehicle exceeds the maximum limit, the drive wheels will spin on the ground due to the adhesive capability between the tyre & ground.
- This adhesive capability is sometimes will be the main limitation of the vehicle performance. This is true when vehicle runs on wet, icy, snow covered or soft soil roads.

Note

The max tractive effort on the driven wheel depends on the longitudinal force that the adhesive capability between the tyre & ground can supply, rather than the max torque that the engine can supply.

Various results shown that the max tractive effort of the driven wheel is closely related to the slipping of the running wheel.

This is also true for dry, good paved roads due to the elasticity of the tyre.

Slip of the tyre is defined as

$$S = \left(1 - \frac{V}{r\omega}\right) \times 100\% = \left(1 - \frac{r_e}{r}\right) \times 100\%$$

where V → translatory speed of the tyre Center.

ω → angular speed of the tyre

r → rolling radius of the free rolling tyre

r_e → effective rolling radius which is defined as $\left(\frac{V}{\omega}\right)$

Interaction, the Speed is less than $r\omega$

∴ Slip of the tyre has a positive Value between 0 and 1.0.

During braking Slip(S) = $\left(1 - \frac{r\omega}{V}\right) \times 100\%$

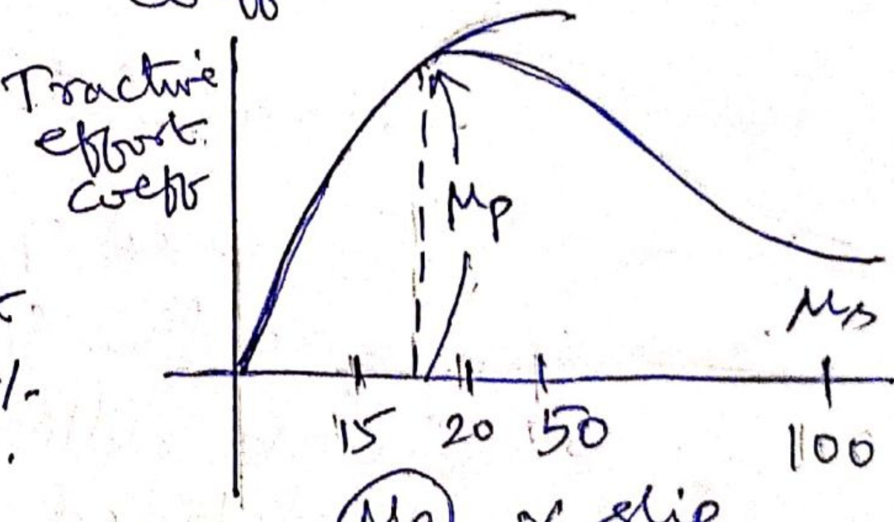
$= \left(1 - \frac{r}{r_e}\right) \times 100\%$.

which has a +ve value between 0 & 1.0 similar to traction.

The maximum traction effort of a tyre corresponds to a certain tyre slip & is usually expressed as

$F = P\mu \longrightarrow$ tractive effort coeff.

P ↙ vertical load of the tyre



note

Peak tractive effort reaches at 15 to 20% slip.

For normal driving slip must be limitted in range less than 15-20%.

μp

μs sliding values

Asphalt & Concrete dry	0.8-0.9	0.75
Concrete (wet)	0.8	0.7
Asphalt (wet)	0.5-0.7	0.4-0.6
Grave	0.6	0.55
Earth road dry	0.68	0.65
wet	0.55	0.4-0.5
Snow hard ice	0.1 to 0.2	0.07-0.15

⑥ Power Train Tractive Effort & Vehicle speed.

- Automobile Power Train consists of a Power source (Engine or electric motor), a clutch in mannual transmission or a torque Converter in automatic trans-mission (trm), a gear box (trm), final drive, differential, drive shaft & driven wheel

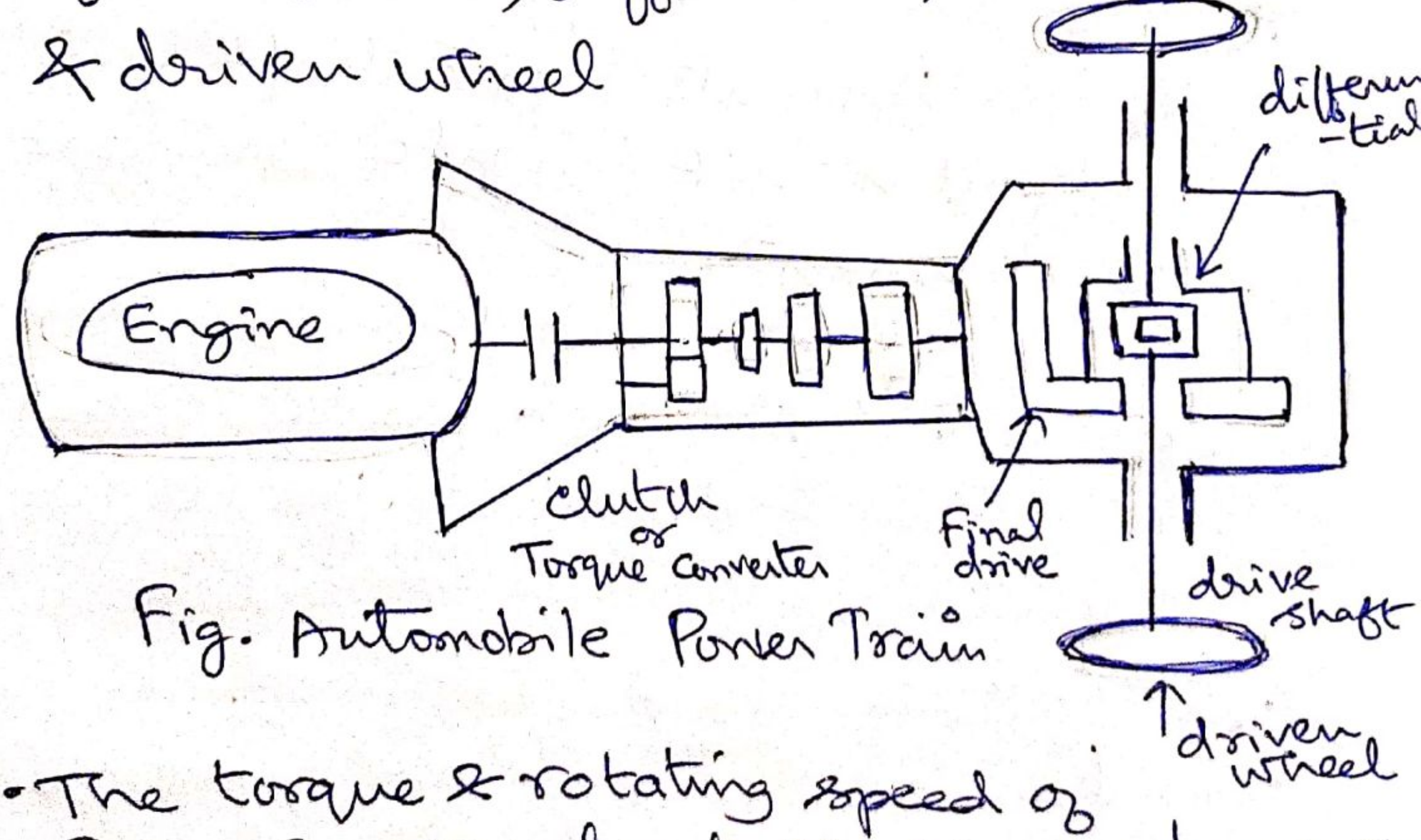


Fig. Automobile Power Train

- The torque & rotating speed of Power source output shaft are transmitted to the drive wheels through the clutch (or) torque converter, gearbox, final drive differential and drive shaft.

- The Clutch is used in manual trm to Couple the gear box to (or) decouple it from the Power Source.
- The torque converter in automatic trm is a hydro dynamic device, functioning as the clutch in manual trm with a continuously Variable gear ratio.
- The gear box Supplies a few gear ratios from its input shaft to its output shaft to match the load requirements.
- The final drive is usually a pair of gears that supply a further speed reduction & distribute the torque to each wheel through the differential.

The Torque on the driven wheels which was transmitted from power source is given by

$$T_w = i_g \, i_o \, \eta_t \, T_p \longrightarrow ①$$

where $i_g = \dfrac{N_{in}}{N_{out}} = \dfrac{\text{input rotating Speed}}{\text{output rotating Speed}}$

↙ gear ratio of the trm.

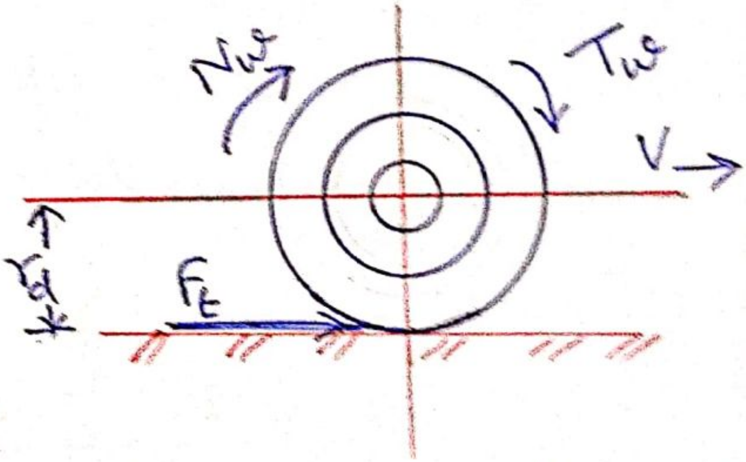
$i_0 \rightarrow$ gear ratio of the final drive

$\eta_t \rightarrow$ efficiency of the drive line from power source to the driven wheels.

$T_p \rightarrow$ torque output from the power source

Tractive effort on the driven wheel

$$F_t = \frac{T_w}{r_d} \rightarrow ②$$



Substitute equ ① in ②

$$F_t = \frac{T_p \, i_g \, i_0 \, \eta_t}{r_d} \rightarrow ③$$

The friction in the gear teeth & the friction in the bearings create losses in mechanical gear trm.

Mechanical efficiency of Various Components

Clutch 99%

Each pair of gears 95–97%

Bearing and joint 98–99%

Total mech efficiency of the trm between the engine output shaft and driven wheels (or) Sprocket is the product of the efficiencies of all the Components in the driveline.

The following average values of the overall mech efficiency of a manual gear-shift trm be used.

Direct gear 90% & other gears 85%

Trm with very high reduction ratio 75-80%

The rotating speed of the driven wheel in rpm $= N_w = \frac{N_p}{i_s\, i_o}$

where $N_p \rightarrow$ output rotating Speed.

The vehicle speed (or) translational speed on the wheel center

$$V = \frac{\pi N_w r_d}{30} \text{ (m/s)} \rightarrow ⑤$$

substituting eqn ④ in ⑤

$$\boxed{V = \frac{\pi N_p r_d}{30\, i_s\, i_o}} \rightarrow ⑥$$

Vehicle Power Source Characteristics.

- There are two limiting factors to maximize tractive effort of a vehicle

Tyre-ground Cohesion (Tyre-ground Contact support)

Torque on a driven wheel

$$F_{t\,max} = \frac{\mu M_v g \cos\alpha \left[L_b + f_r(h_g - r_d)\right]/L}{1 + \mu\, h_g/L}$$

(or)

$$F_{t\,max} = \frac{\mu M_v g \cos\alpha \left[L_a + f_r(h_g - r_d)\right]/L}{1 + \mu\, h_g/L} \rightarrow ⑧$$

$$\boxed{F_t = \frac{T_p\, i_g\, i_o\, \eta_t}{r_d} \rightarrow ⑦}$$

The Smaller of these two factors will determine the performance potential of the vehicle.

- For on-road vehicle the performace is usually limitted by the second factor.

Inorder to predict the overall performance of the vehicle its power source & trm charateristics must be taken into consideration.

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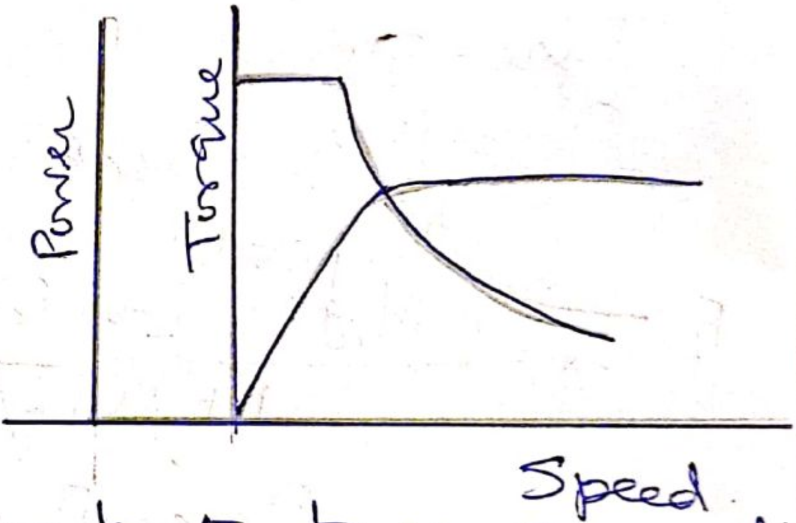
Power Source Charateristics

- The ideal performance charateristics of a power source is the constant power output over the full speed range



- At low speeds, the torque is constrained to be constant so as to limit the value less than maximum value which can be done by the tyre-ground cohesion.

- The constant power characteristic provides the vehicle with hight tractive effort at low speeds (especially for grade climbing capability)

- For vehicle ICE and electric motors are most commonly used power sources

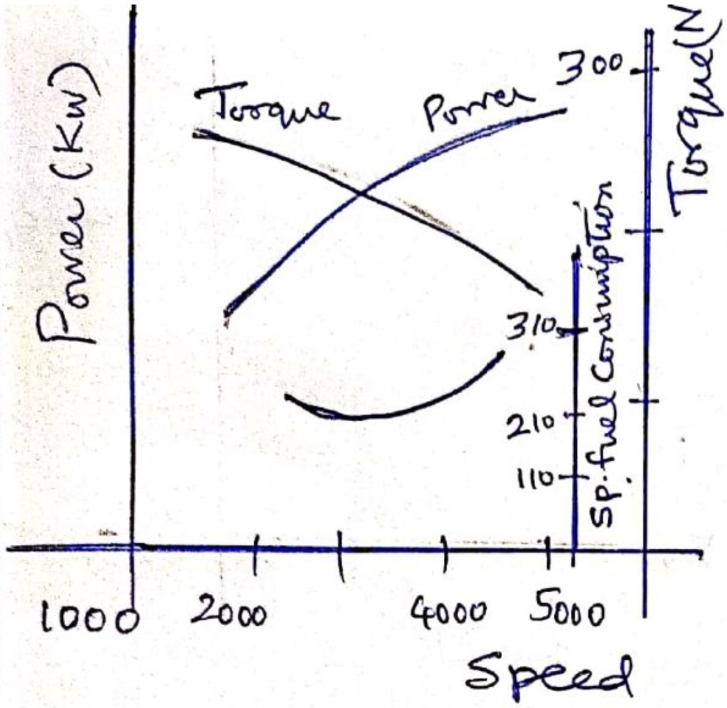


Fig Typical performance Characteristics of Gasoline Engine.
Speed Vs Power
Specific fuel Consumption
Torque.

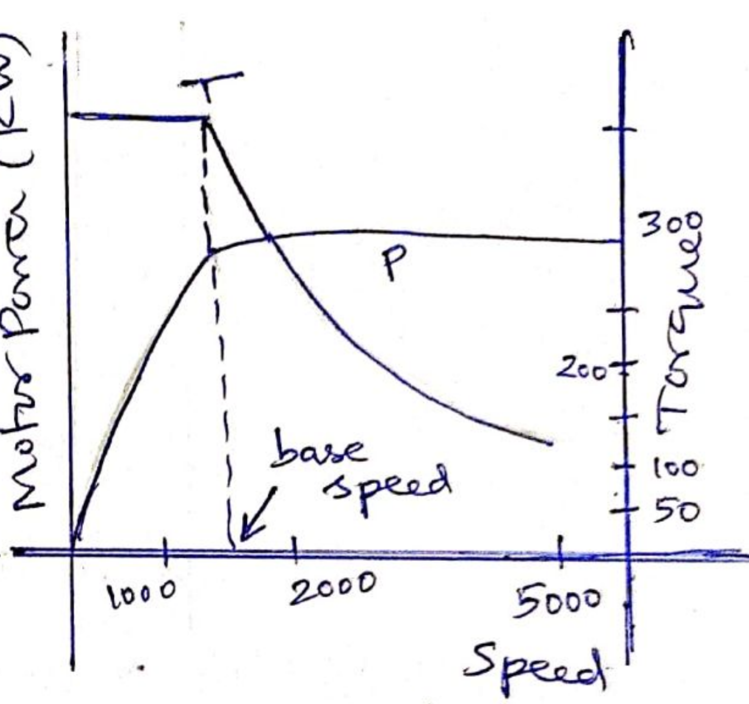


fig. Typical performance characteristics of Electric motor

- Generally electric motor Starts from Zero Speed. As it increase to its base speed, the voltage increase to its rated value while the flux remains Constant.
- Beyond the base speed, the voltage remain Constant & the flux is weakened. This results in Constant output power while the torque declines hyperbolically with speed.

- As the electric motor Speed - Torque characteristic is close to ideal is necessary a single gear or double gear trm is usually employed.

Trm Characteristics:

- The Transmission (Trm) requirements of a Vehicle depends on
  ① the Characteristics of the power source
  ② performance requirements of the vehicle.

- Mutigear Trm is not required for a well Controlled electric machine.

- But an ICE must have a multigear or Continously Varying trm to multiply its torque at low Speed.

There are two basic types of trm:

① Manual gear Trm
② Hydro dynamic Trm.

⑦ Manual Gear Trm:

(Refer Automobile Power Train)

- This consists of clutch, gearbox, final drive & drive shaft.
- The final drive has a constant gear reduction ratio (or) differential gear ratio.
- The direct drive (non-reducing) in the gearbox is the highest gear in use.
- The gearbox provides a number of gear reduction ratios ranging from 3 to 5 for passenger cars & more for heavy commercial vehicles that are powered by gasoline or diesel engines.
- The maximum speed requirement of the vehicle determines the gear ratio of the highest gear (i-e smallest ratio)
- On the other hand the gear ratio of the lowest gear (ie max ratio) is determined by the gradebility (or) max tractive effort requir -ement

- The ratio between them should be spaced in such a way that they will provide the tractive effort – speed chara close to ideal chara.

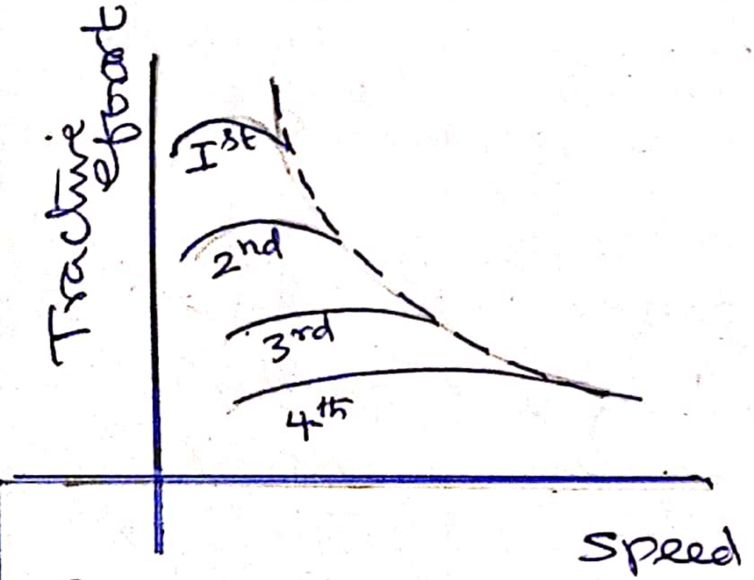
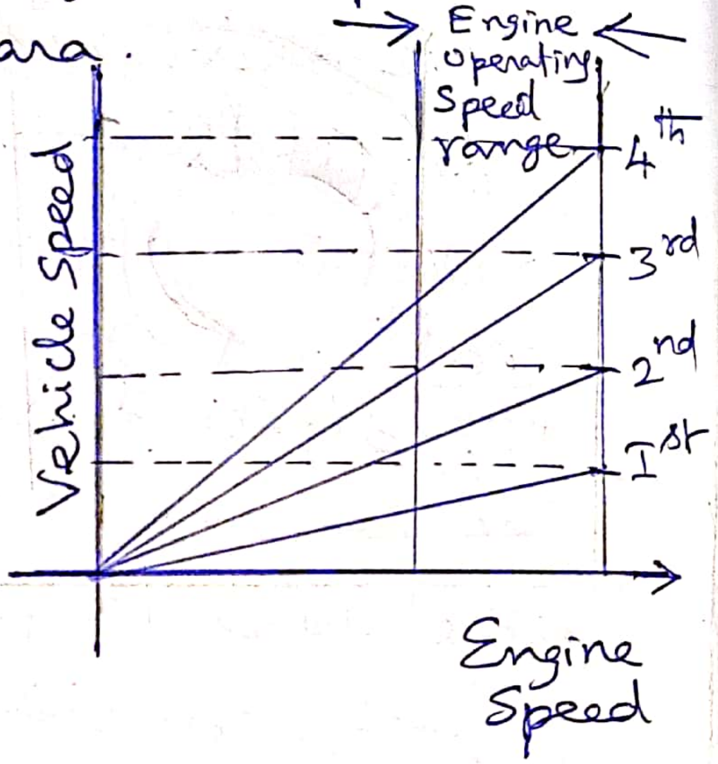


Fig. Tractive effort chara of gasoline engine Powered Vehicle.



- During normal driving proper gear can be selected according to the requirement & to operate the engine in its optimum speed range for fuel saving purposes.

For 4 speed gearbox ⇒ $\frac{i_{g1}}{i_{g2}} = \frac{i_{g2}}{i_{g3}} = \frac{i_{g}}{i_{g4}} = k_g$ → ⑨

where $i_{g1}, i_{g2}, i_{g3}, i_{g4}$ are the gear ratio for 1, 2, 3 & 4th gears respectively

$$K_g = \sqrt[3]{\frac{i_{g_1}}{i_{g_4}}} \longrightarrow ⑩$$

- If the ratio of highest gear i_{gs} (small gear ratio) & the lowest gear i_{gh} (high gear ratio) have been determined & the number of gears (N) (or) (n_g) is known then

$$K_g = \left(\frac{i_{gh}}{i_{gs}}\right)^{(N-1)} \text{ or } \left(\frac{i_{gh}}{i_{gs}}\right)^{n_g-1} \longrightarrow ⑪$$

& each gear ratio can be found

$$i_{gs-1} = K_g \, i_{gs} \text{ (or) } (i_{gh})^{N-1} = K_g \, i_{gs} \longrightarrow ⑫$$

For passenger cars, to suit changing traffic conditions, the step between the ratios of the upper 2 gears is often a little closer than to eqn ⑫

i.e. $$\frac{i_{g_1}}{i_{g_2}} > \frac{i_{g_2}}{i_{g_3}} > \frac{i_{g_3}}{i_{g_4}} \rightarrow ⑬$$

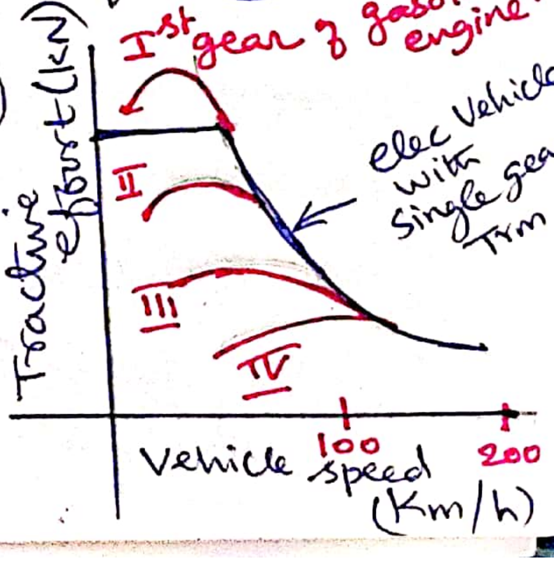


Fig: Tractive Effort of vehicle with gasoline engine & electric motor with single gear Trm.

Hydrodynamic Transmission.

- This uses fluid to transmit power in the form of Torque (T) and Speed (N) & are widely used in passenger cars.

#This Consists of

- Torque Converter
&
- Automatic gearbox

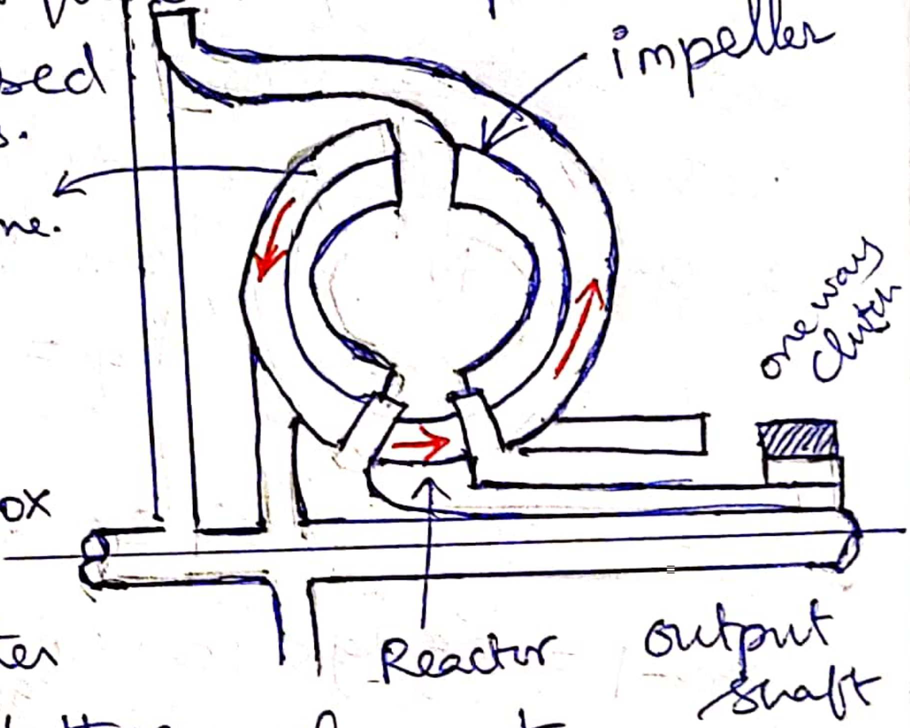


Fig. Torque converter

The torque Converter consists of atleast three elements Impeller (pump), Turbine, & reactor.

- The Impeller is Connected to the engine shaft & the turbine is Connected to the output shaft of the Converter, which inturn is Coupled to the input shaft of the multi speed gearbox.
- The reactor is coupled to the external housing to provide a reaction on the fluid circulating in the Converter.

- The reactor is usually mounted on a free wheel (one way clutch) so that when the starting period has been completed & the turbine speed is approaching that of the pump, the reactor is in free rotation.
- At this point, the converter operates at a ratio of output torque to input torque = 1.0.

Performance characteristics of Torque Converter depends on the following

① Speed Ratio (C_{sr}) = $\frac{\text{output Speed}}{\text{Input Speed}}$ → ⑭

↙ reciprocal of gear ratio

② Torque Ratio (C_{tr}) = $\frac{\text{output torque}}{\text{Input torque}}$ → ⑮

③ Capacity factor (K_{tc}) = $\frac{\text{Speed}}{\sqrt{\text{Torque}}}$ → ⑯

↙ ability to convert to absorb (or) transmit torque, which is proportional to the square of the rotary speed

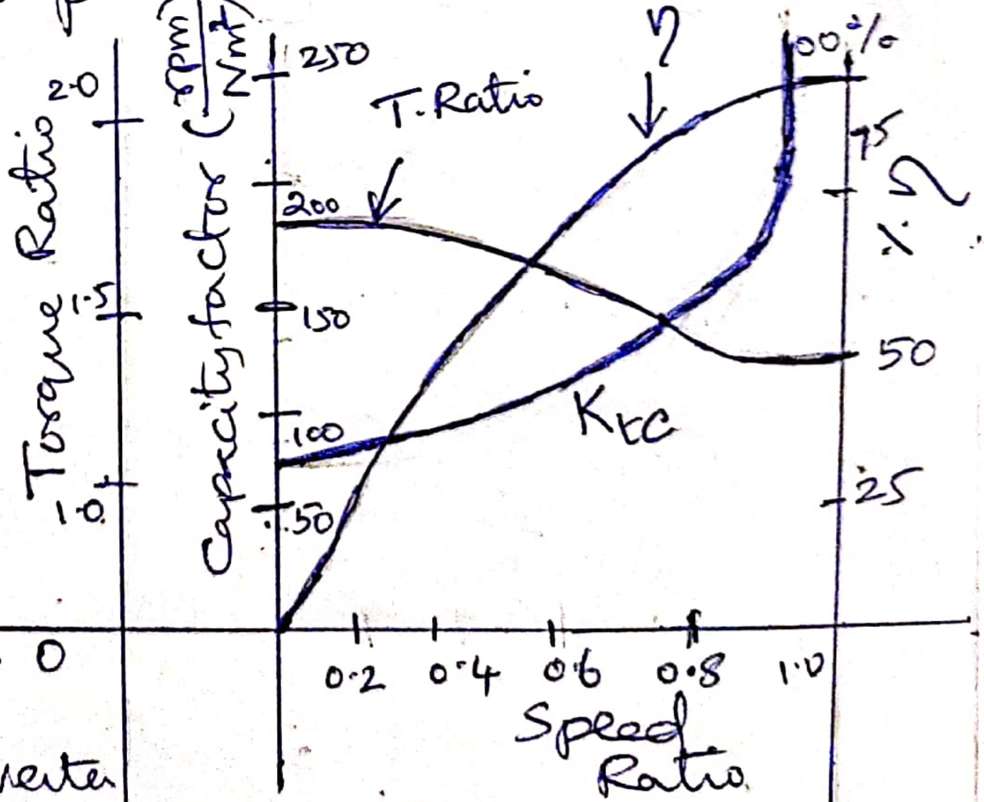
④ Efficiency = $\frac{\text{output Speed}}{\text{Input Speed}} \times \frac{\text{output torque}}{\text{Input torque}} = C_{sr}\, C_{t}$ → ⑰

Advantages of hydrodynamic Trm

- Engine will not stall when properly matched.
- Provides flexible Coupling between engine & the wheels.
- With suitably selected multi speed gearbox, it provides Torque-Speed Chara similar to ideal Condition.

Disadvantages:

- Low efficiency in a stop-go driving Pattern
- Have Complex Construction.



- The Torque ratio has a max value at stall condition (output speed is zero)
- Torque ratio decreases as the gear ratio decreases (or) speed ratio increases & Converter usually acts as a hydraulic coupling with

torque ratio of 1.0. At this point, a small difference between the input & output speed exists because of the slip between the impeller (pump) & turbine.

- The efficiency of the Torque Converter is zero at stall condition & increases with increasing speed ratio & reaches max when the converter acts as a fluid coupling. (torque ratio = 1)
- The engine operating point is to be specified to determine the combined performance of the engine & the converter using engine capacity factor

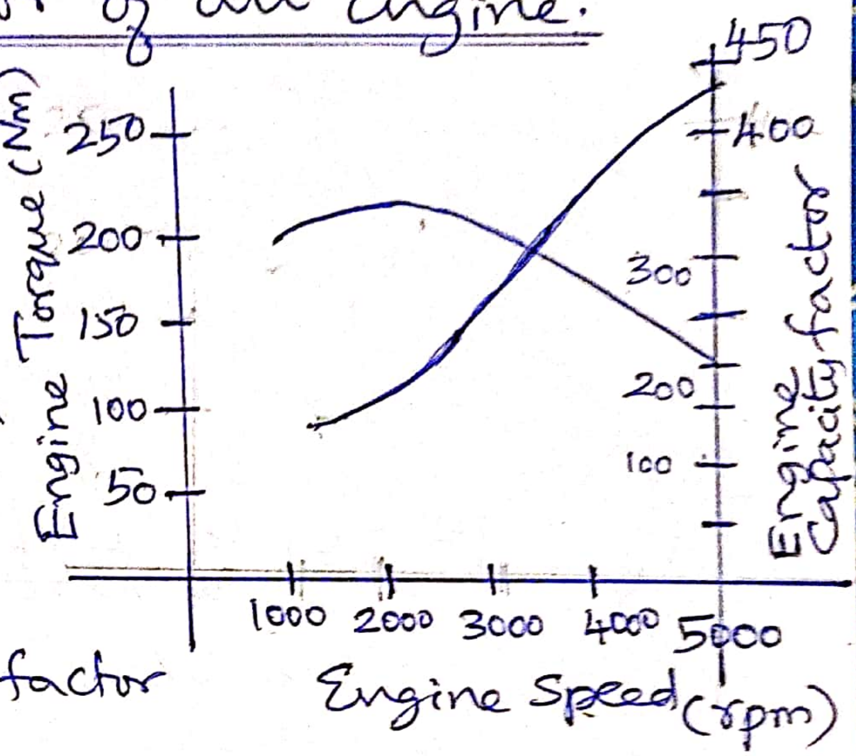
$$K_c = \frac{n_e}{\sqrt{T_e}} \longrightarrow ⑱$$

where n_e & T_e are speed & torque of the engine.

- To achieve proper matching, the engine & torque converter should have a similar range in the capacity factor

——x——

⑧ Capacity factor of an Engine.



- The Engine shaft is usually connected to the input shaft of the torque Converter

$$K_c = K_e \longrightarrow ⑲$$

K_c → Capacity factor.

K_e → Engine Capacity factor

The output torque & output speed of the Converter $T_{tc} = T_e C_{tr} \longrightarrow$ ⑳

C_{tr} → Torque ratio

and output speed of the Converter

$$n_{tc} = n_e C_{sr} \longrightarrow ㉑$$

C_{sr} → Converter speed ratio

- As the torque converter has a limited torque ratio range (usually less than 2) a multi speed gearbox is usually connected to it.
- The gearbox comprises several planetary gearsets and is automatically shifted.

- With the gear ratios of the gearbox, the tractive effort and the speed of the vehicle can be calculated from eqns ① & ⑥

$$T_w = i_g i_o \eta_t T_p \qquad V = \frac{\pi N_p r_d}{30 i_g i_o}$$

$$F_t = \frac{T_e C_{tr} i_g i_o \eta_t}{r} \quad \& \quad V = \frac{\pi n_e C_{sr} r}{30 i_g i_o} \ (m/s)$$

$$= \frac{0.377 n_e C_{sr} r}{i_t} \ (Km/h) \qquad ㉒$$

—×—

Continuously Variable Transmission (CVT)

- This has a gear ratio that can be varied continuously within a certain range, thus providing an infinity of gear ratios.
- This continuous variation allows for the matching of virtually any engine speed and torque to any wheel speed & torque.

- Commonly used CVT is done by a Pulley and belt assembly. one pulley is Connected to the engine Shaft, while the other is Connected to the output Shaft.
- The belt links the 2 pulleys.
- The distance between the two half pulleys can be Varied, thus Varying the effective diameter on which the belt grips.

The transmission ratio $i_g = \frac{D_2}{D_1}$

$= \frac{\text{diameter of output pully}}{\text{diameter of input pulley}}$

- Metallic belts is being used nowadays to provide better solidity & improved Contact between belts & pulleys.
- Nissan four wheeler Company had developed a Concept used with 3 friction gears
  - ① Connected to engine shaft
  - ② to the output shaft
  - ③ the 3rd gear grips on a particular profile of the other two gears.

- It can have a rotation with grip on different effective diameter & therefore achieving a variable gear ratio

Vehicle Performance:

- This is described by its maximum cruising, speed, gradeability & acceleration.
- This is based on the relationship between tractive effort & vehicle speed
- For on-road vehicle, it is assumed that the maximum tractive effort is limitted by the maximum torque of the power source rather than road adhesion capability.
- from eqns $F_t = \dfrac{T_p \, i_g \, i_o \, \eta_t}{r_d}$ → ③ &

Tractive effort

Speed $V = \dfrac{0.377 \, \eta_e \, C_{sr} \cdot r}{i_t}$ → ㉒

Road resistance $(F_r + F_w + F_g)$ → grading resi $= M_v g \sin\alpha$

rolling resi $= P f_r \cos\alpha$

resi due to aerodyn drag $= \frac{1}{2} \rho A_f C_D (V + V_w)^2$

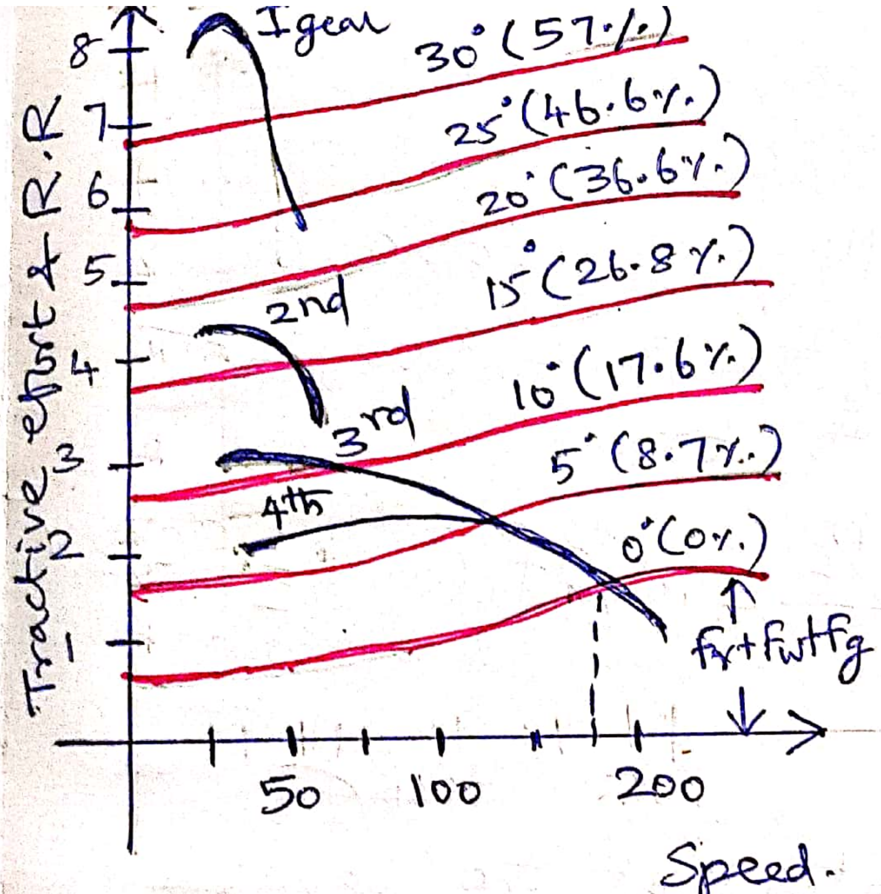


Fig. Tractive effort & Road Resi (RR) of the Vehicle powered with gasoline engine with multi speed Trm.

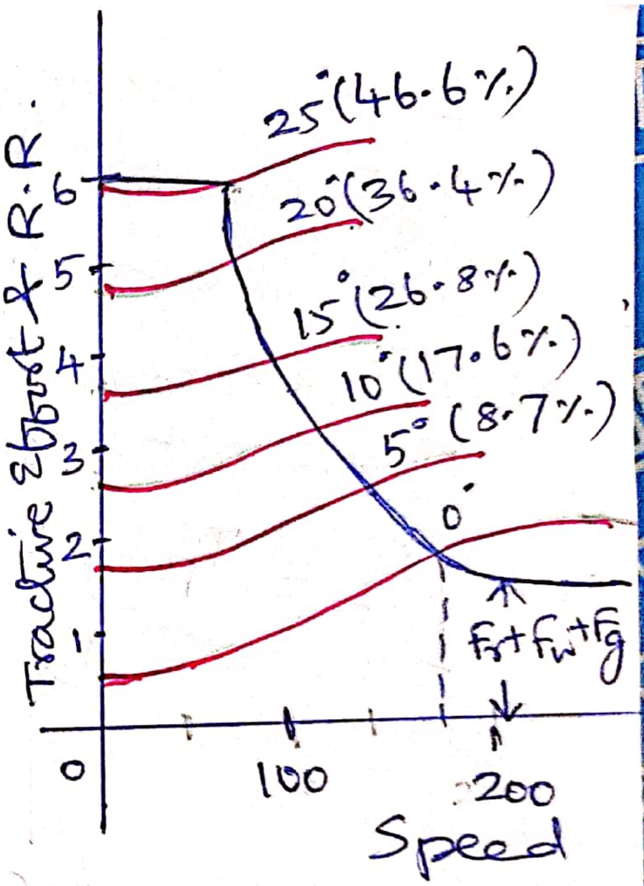


Fig. Tractive Effort & Road Resi (RR) of the vehicle powered with electric motor.

Maximum Speed of a Vehicle:

- It is defined as the constant cruising speed that the Vehicle can develop with full power source load (full throttle of the engine or full power of motor) on a flat road.

- It is determined by the equilibrium between the tractive effort of the vehicle & rolling resistance (or) max speed of the power source & gear ratio of the trm.

$$\underset{\text{Tractive Effort}}{F_t} = \frac{T_p i_g i_0 \eta_t}{r_d} = M_v g f_r \cos\alpha + \underbrace{\frac{1}{2}\rho_0 C_D A_f V^2}_{\text{grading resi}} \longrightarrow ㉓$$

- Equ ㉓ indicates that the vehicle reaches its max speed when the Tractive Effort equals rolling resistances
- From the above two figures, the intersection point of the Tractive Effort & Rolling Resistance represents the max speed of the vehicle.
- Some vehicles due to its large power source (or) large gear ratio no intersection point exists. then the maximum speed of the vehicle is determined by the max speed of

the power source.

$$V_{max} = \frac{\pi \, n_p \, r_d}{30 \, i_{g_{min}} \, i_o} \quad (m/s)$$

max speed

minimum gear ratio of the trm.

Gradeability:

- It is defined as the grade (grade angle) that the vehicle can overcome at a certain constant speed (or) defined as max grade (grade angle) in the whole speed range especially for heavy commercial vehicle (or) off-road vehicle.

Tractive and Rolling Resistance equation

$$\frac{T_p \, i_o \, i_g \, \eta_t}{r_d} = M_v g f_r + \frac{1}{2} \rho_o C_D A_f V^2 + M_v g i \longrightarrow ㉔$$

$$i = \frac{\left[\frac{T_p \, i_o \, i_g \, \eta_t}{r_d}\right] - M_v g f_r - \left(\frac{1}{2} \rho_o C_D A_f V^2\right)}{M_v g}$$

$$i = \left[\underbrace{\frac{T_p \, i_o \, i_g \, \eta_t}{M_v g \, r_d} - \frac{\left(\frac{1}{2} \rho_o C_D A_f V^2\right)}{M_v g}}_{\text{Performance factor}}\right] - f_r \longrightarrow ㉕$$

where Performance Factor (PF)

$$= \frac{F_t - F_w}{M_v g} = \left[\frac{T_p i_o i_g \eta_t}{M_v g r_d} - \frac{\left(\frac{1}{2} \rho_o C_D A_f V^2\right)}{M_v g}\right]$$

Vehicle drives on a road with a large grade, the gradeability of the vehicle be calculated as.

$$\sin\alpha = \frac{(PF) - f_r\sqrt{1-(PF)^2 + f_r^2}}{1+f_r^2} \rightarrow ㉖$$

where $f_r =$ rolling resi Coeff $= \frac{a}{r_d}$

(or) Can be obtained from the above two graphs.

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⑨ Acceleration Performance

- It is usually described by the vehicle's acceleration time & the distance covered from zero to certain high speed on level ground.
- Using Newton's 2nd law the acceleration of the vehicle will be

$$a = \frac{dv}{dt} = \frac{F_t - F_{fr} - F_w}{M_v \delta} \longrightarrow \text{㉗}$$

where V → speed of the vehicle

F_t → Total Tractive Effort of the vehicle

F_r (or) F_{fr} → Force due to Rolling Resistance

$$F_{fr} = f = \frac{T_r}{r_d} = \frac{Pa}{r_d}$$

$$= P f_r \xrightarrow{} \text{Rolling resi coeff.}$$

F_w → Force due to aerodynamic drag.

M_v → Total mass of the vehicle.

δ → mass factor which is an effect of rotating components in the power train or power source.

δ → is the Mass factor

Considering equivalent mass increase due to the angular moments of the rotating Components

Total angular moment associated with wheels

$$\delta = 1 + \frac{I_w}{M_v r_d^2} = \frac{i_o^2 i_g^2 I_p}{M_v r_d^2} \longrightarrow$$ ㉘

Total angular moment associated with power Source

• When mass moment of inertia of all rotating parts are not known the following empirical relation is used.

$$\delta = 1 + \delta_1 + \delta_2 i_g^2 i_o^2 \longrightarrow$$ ㉙

δ_1 → Power source

δ_2 → associated with rotating part ≃ 0.0025

From eqn ㉗

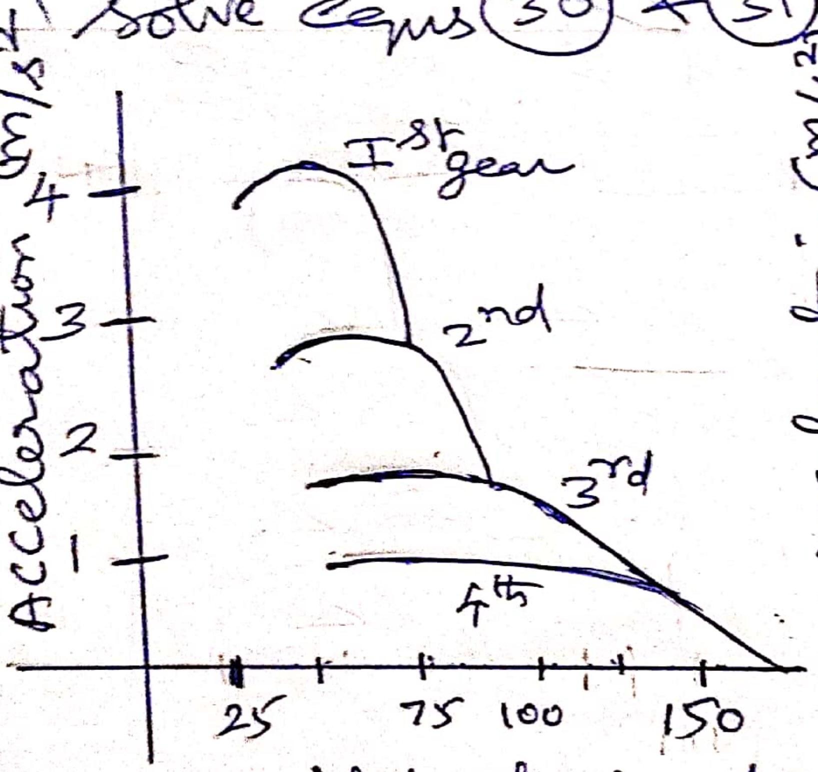
the acceleration time (t_a) and distance (S_a) from low speed (V_1) to high speed (V_2) be

$$t_a = \int_{V_1}^{V_2} \frac{M_v \delta V}{(T_p i_g i_o \eta_t / r_d) - M_v g f_r - (\frac{1}{2} \rho_o C_D A_f V^2)} \longrightarrow$$ ㉚

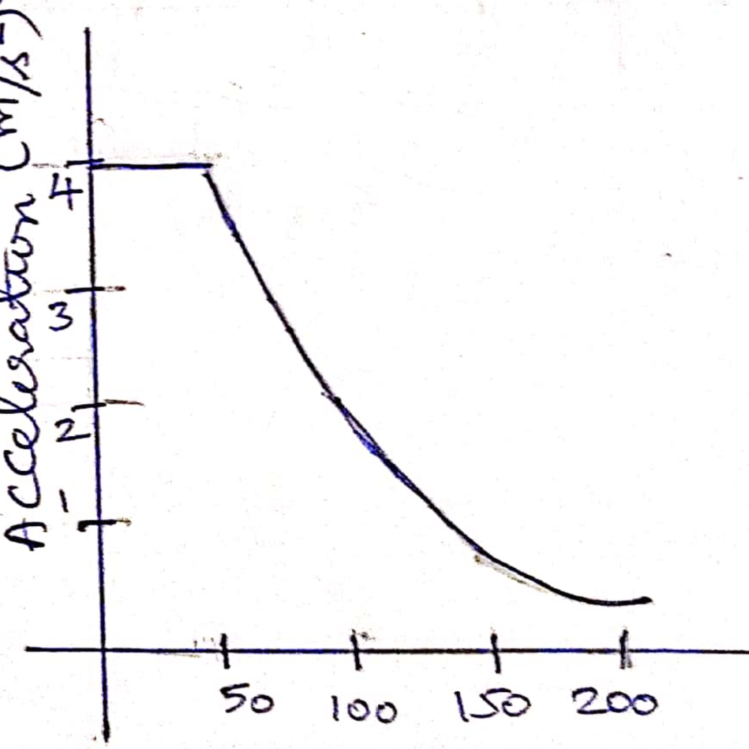
$$S_a = \int_{V_1}^{V_2} \frac{M_v \delta}{(T_p i_g i_o \eta_t / r_d)} \longrightarrow ㉛$$

where Tp is the function of speed which is a function of gear ratio of the trm also.

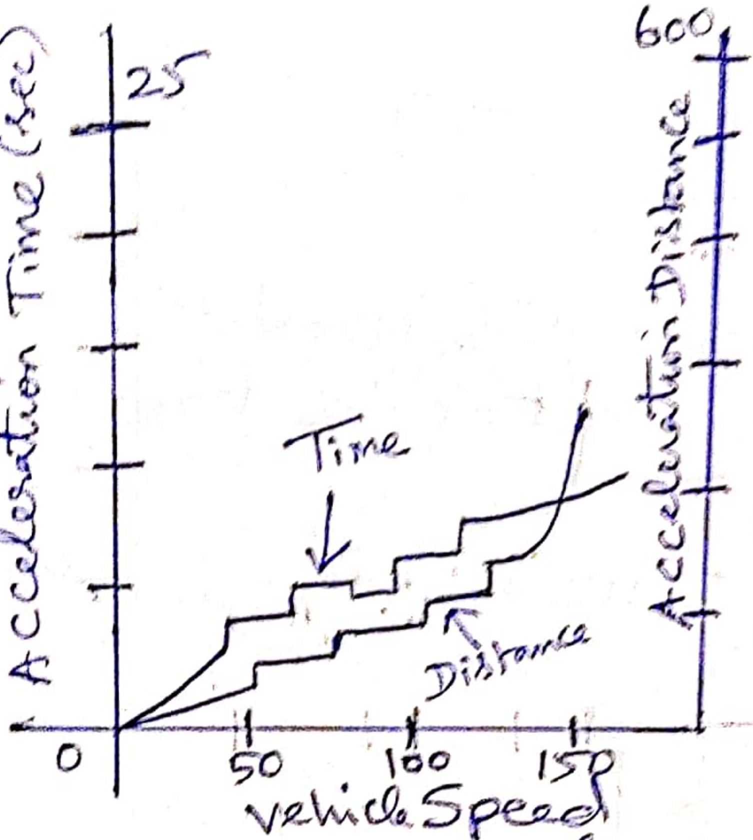
Various numerical methods are used to solve eqns ㉚ & ㉛



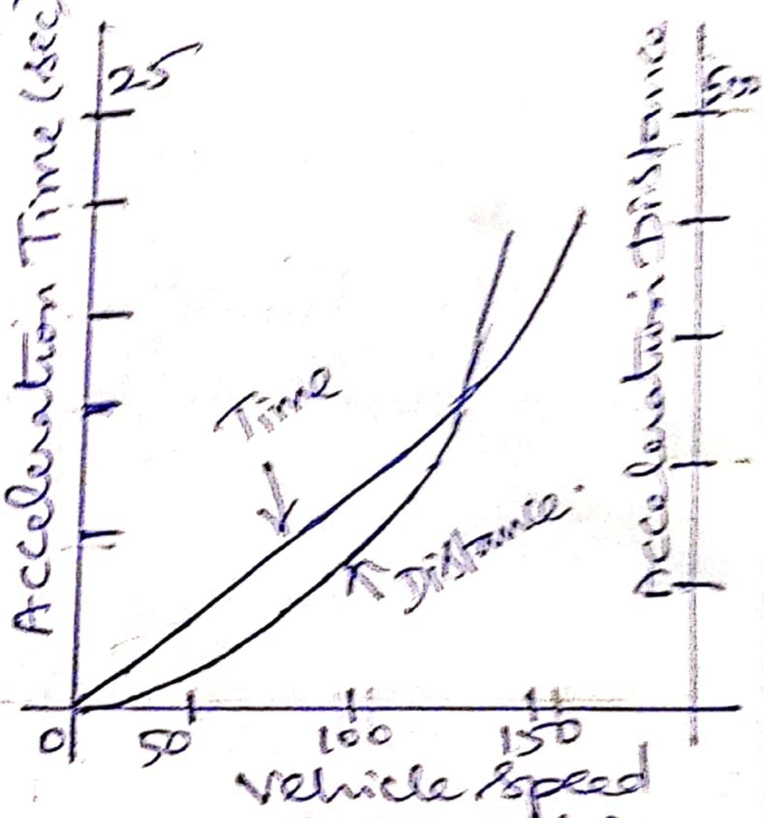
Vehicle speed (Gasoline engine driven)



Vehicle Speed (with elec M/c)



(with gasoline Engine)



(with electric motor)

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Unit-II Hybrid Vehicles.

Introduction to Hybrid Electic Vehicles History of Hybrid & Electic vehicles, Social and environmental importance of Hybrid and Electic Vehicles, impact of modern drive-trains on energy supplies

Hybrid Electic Drive-trains: Basic Concept of hybrid traction, Introduction to various hydrid drive train topologies. Power flow Control in hybrid drive-train topologies fuel efficiency Analysis.

Introduction to Hybrid Electric vehicles.

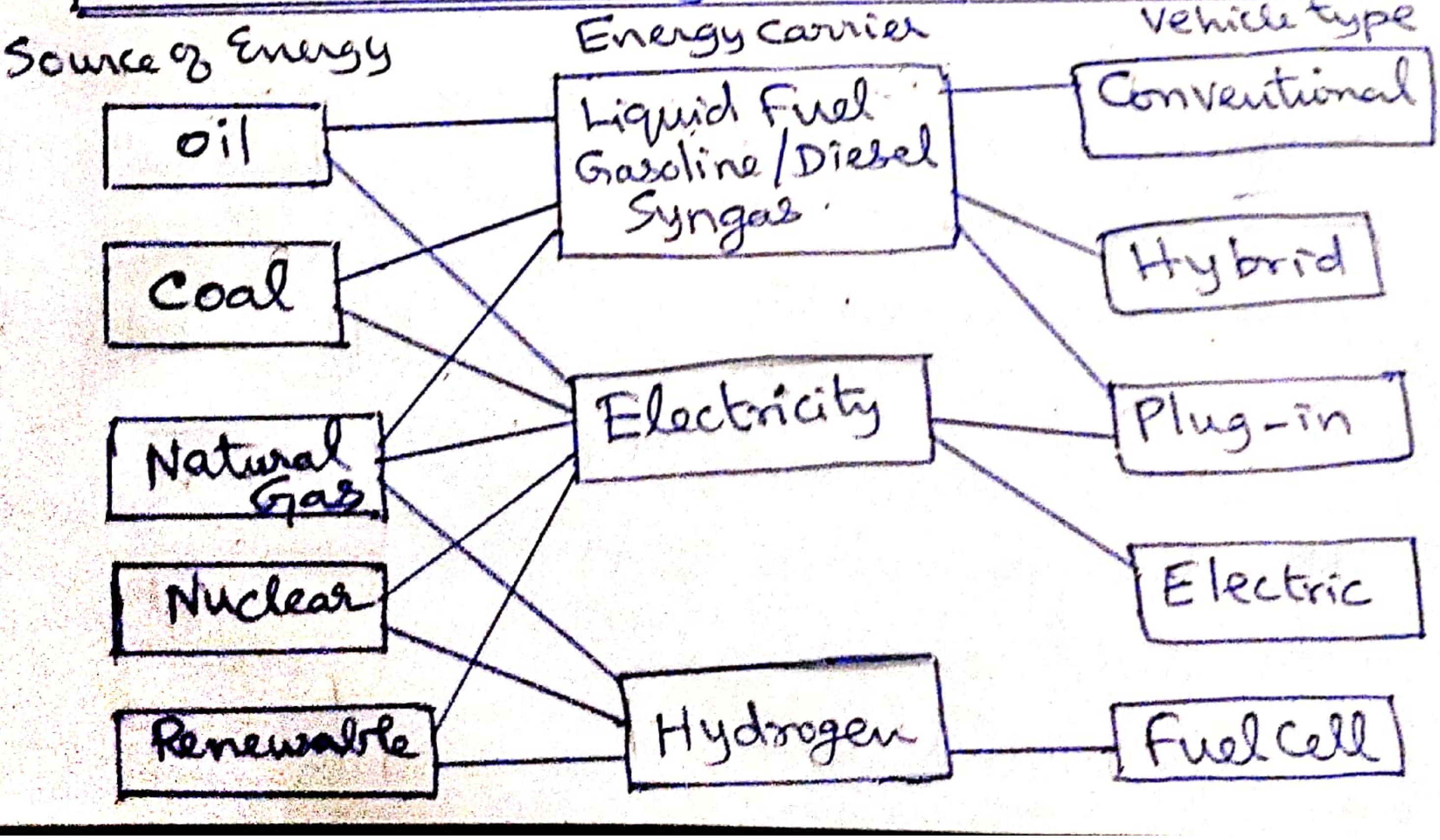
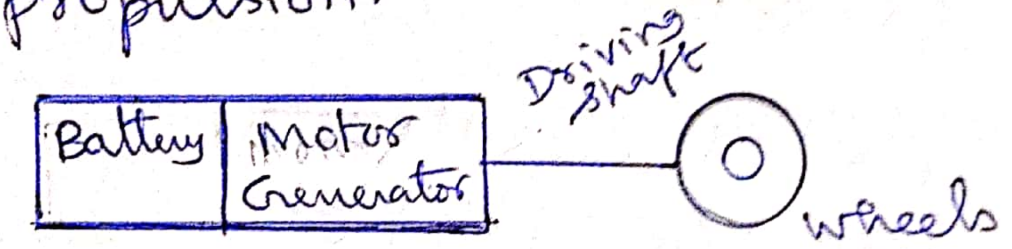


Figure shows the Sustainable Transportation model.

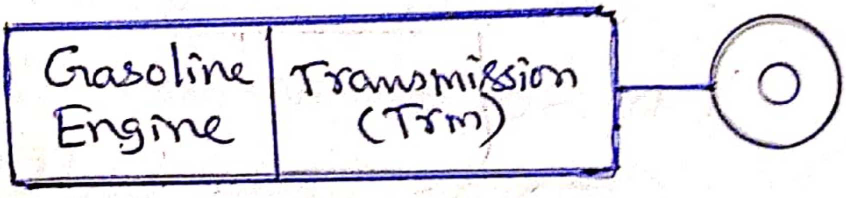
- The primary purpose of hybrid Electric Vehicle (HEV) is not based on low fuel Consumption but to make the Internal Combustion Engine (ICE) to provide an acceptable level of performance.
- Earlier, pure Electric Vehicles could no longer compete with the greatly improved gasoline engines (ICE) came into use after World war I. → or (GE)
- The GE had major improvement in Power density, smaller in size, more efficient & more over there was no need to assist them with electric motor. The supplementary cost of electric motor & hazards associated with the acid batteries were the main factors in the disappearance of pure Electric vehicles (EV) & Hybrid vehicles (HV) in the market after World War I.

<u>Note</u>: Electric Vehicles (EV) also called as Electric Drive vehicles (EDV) uses one or more electric motors or traction motors for propulsion.

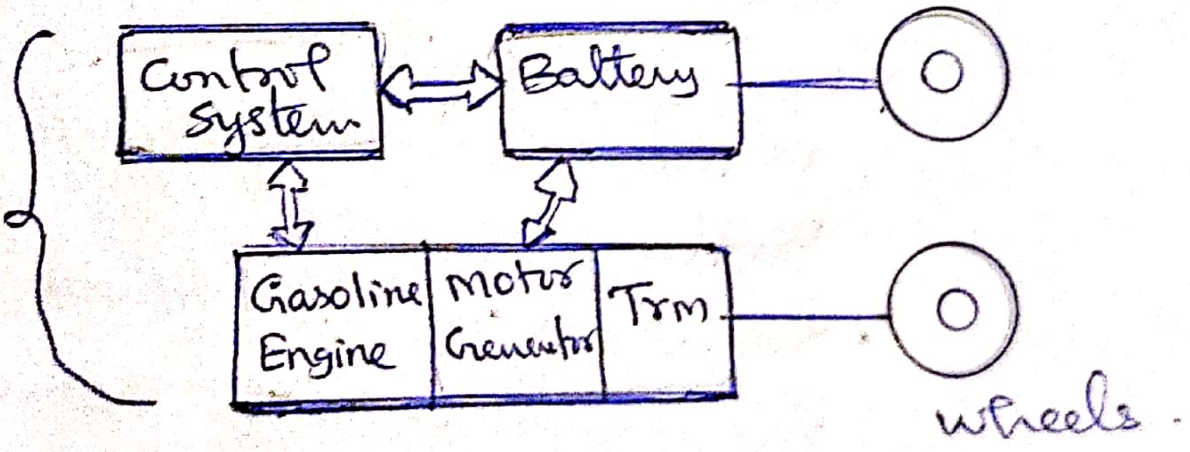
Pure EV

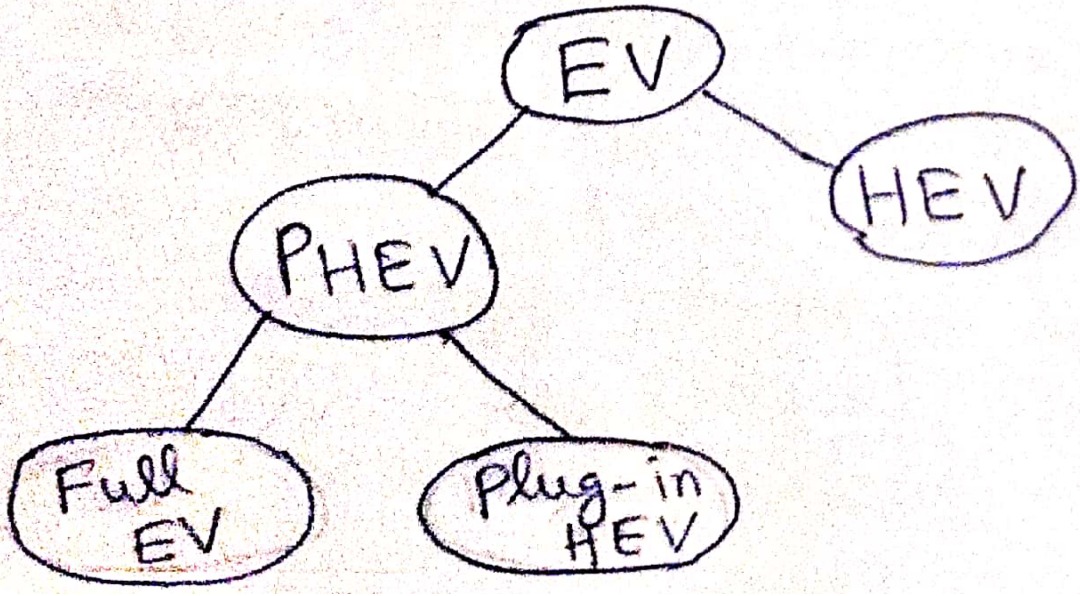


Pure Gasoline Engine.



Hybrid EV.





Pure EV (or) EV were invented in 1834 i.e almost 60 years earlier than gasoline powered vehicle (car) (invented in 1895)

- HEVehicles together with EV faded away by 1930 because
  - Limited range between charges
  - More expensive than gasoline cars as large battery packs were used.
  - Less powerful than Gasoline cars as the power out from on board battery is less.
  - Requires many hours to recharge the on-board batteries.
  - In rural & Urban lack of accessibility for charging the vehicle.
- Oil crises in 1973 US Congress introduced Electric and Hybrid Vehicles Research Development & Demonstration

Act introduced in 1976 to encourage the Production of Electric & Hybrid Vehicles.

- EV failure in 1990s.
  - To ensure Zero Emission Vehicle (ZEV), the EV manufactured had to meet out the requirements mentioned in the California Air Resources Board (CARB) (due to Smog formation due to ICE) Act.
  - Several Companies like GM, EV, Toyota, Ford Ranger were well known EV manufacturers had failed in Promoting EV production in 1990s.

The major reasons were.

- Limitations of EV.
  - Limited range (EV provides 96 - 160 Kms Compared to 480 Kms or more from gasoline powered engine)
  - Long Charging time (8 or more hours)

- High cost (40% more expensive than gasoline cars)
- Limited cargo space.
- <u>Capital investment</u>: The operating fuel cost is insignificant when compared to the capital investment done for buying EV.
- <u>Consumer's mindset</u>
  - Consumers preferred Sports Utility Vehicle (SUV) than small efficient vehicle due to low price gasolines.
  - Consumers believe that large SUV & pickup trucks were safe to drive & convenient (towing)
- <u>Car Manufacturers</u>:
  - Several Billion dollars were spent for the research and development of EVs by the car manufacturers But the market did not respond very well.

- maintenance & Servicing were addisional burden to the dealership holders.
- Liability was a major concern, though there was no evidence that the EVs were less safe than gasoline powered vehicles.
- EVs were seen as a threat to gas and oil Industry, the Government dropped the CARB's Law. The last minute switching from mandate for EVs to hydrogen powered vehicle.

- Battery Technology:
  - Lead acid batteries were used in most of the EVs during 1990s.
  - The batteries were found to be huge & heavy & more time is required for charging.
  - There were limitted infrastructure for recharging the batteries.

Pure EV

- It has an motor/generator which allows regenerative braking.
- Powered directly by electricity rather than a Combustible fuel.
- EV have an array of rechargable batteries/atleast one electric motor, a Controller to feed the motor & a Charging system.
- To reduce the severe air pollution, Zero Emission EV has been developed which are powered by on-board batteries.
- Fuel cell EV is found to be the long term potential vehicle.
- EV structure have 3 main parts
  - Energy Source (Rechargable battery
Ultracapacitor
Fuel cell)
  - Power Converter (adjusts the voltage according to load demand)
  - Traction motor.

② • EV operated with electric power only.

• Mostly Lithium battery is widely used. Battery charges with grid.

• Most of the EV in the market operates 128-240 kms electrical range. In near future 480-640 kms is expected. Battery 80kWh storage capacity.

• EV costs approximately $360/year to operate compared with $3600/year for gasoline powered vehicle.

• EV three types.

Battery EV   Plug-in EV   HEV

Note Pure gasoline vehicles :→ fuel tank, fuel lines, fuel injection system, cooling system & exhaust system.

Hybrid EV :

- This is formed by merging Components from a pure EV and a pure gasoline Powered Vehicle.
- Motor/Generator (M/G) installed in this enables regenerative braking
- Here M/G is tucked directly behind the engine. then transmission appears.
- Has two torque producers M/G in motor mode & gasoline engine plus Battery & M/G.
- In HEV addisionally 3 main power sources are available.
  - <u>Batteries</u> :- provides both modest power & energy.
  - <u>Fuel cell</u> : provides high energy but low power.
  - <u>Capacitor</u> (ultra capa) : provides very large power but low energy.

- Presently HEV is provided with rechargable battery on board, gasoline Engine-generator or a hydrogen fuel cell.
- EV combined with solar panels on the roof will result in zero running cost, apart from super chargers stations (even one hour is sufficient when compared with conventional 8 hours normal charging)
- EV with $2.64 for full charging which can make it to run 112 kms.

— × —

EV ⇒ Battery EV

- This runs entirely using elec motor & battery with/without the support of ICE
- Charging can be done by regenerative braking

Advantages	Disadvantages
• No emission • No gas (or) oil changes • Can be charged in homes • Fast & smooth acceleration. • Low cost operation $30/month.	• Short range than gasoline vehicle. • Slightly more expensive than ICE

BEV

Vehicle	Capital Cost of the Vehicle	Kms.	Charging Time
Tesla	$83000 — 125000	335 – 426	5 hours
Nissan	$ 32000/-	120	3 hours
BMW i3 (4 seater)	$ 45,000/	160	6 hours
mitsubishi (5 seater)	$ 28000/-	100	7 hours
Smart EV (2 seater)	$ 27000/-	109	6 hours
Ford Focus EV (5 seater	$ 37000/-	110	4 hours

- Plug-in HEV (or) Grid Connected HEV (or) Vehicle to Grid [V2G]
  - uses an electric motor & battery that can plugged into power grid to Charge the battery & has a support of an ICE that may be useful to recharge the vehicle's battery and/to replace the electric motor when the battery has low Charging.
- It is full hybrid and able to run in electric mode only with larger batteries and able to recharge from electric power grids.
- As PHEV uses power from grids & often more savings in the fuel cost than traditional HEV
- |||r. to Full HEV regenerative braking improved economy & dynamic performance & also reduced emission.

- The main advantage of this V2G is that it can be gasoline-independent as it have extended range of hybrid for long trips.
- designed as charge depleting: Part of the 'fuel' consumed during a drive is delivered by the utility preference at nights.
- "Fuel efficiency" ⇒ calculated by the actual fuel consumed by the ICE. If the hybrid has ICE, the ICE serves only for supplying the elec power through the generator for long drive distances.
- PHEV made with multifuel, with the electric power supplemented by diesel biodiesel or hydrogen.
- Hydrogen powered EV has a total efficiency of 13% only but battery powered EV achieves an efficiency of 50 - 60%.

PHEV

Advantage	Disadvantages.
• Long range than BEV • Less gas consumption than gas only vehicle. • less emission • Simple mechanism • With Power Capacity of 80–150 KW when operates in electrical mode can run 32-96 Kms. • During driving route vehicle operates in electrical mode (using stored energy in battery) than ICE is made to operate.	• Produces tail pipe emissions. • Needs gas & oil Changes. • More expensive than BEV but less than traditinil HEV

PHEV	Capital Cost	Kms run.	Charging Time.
BMW i3 Rex (4 seater	$50000/-	160 kms on elec + 160 kms on gas	6 hours.
BMW i8	$136000/-	37 on electrical	2 hours
Cadillac ELR (4 seater)	$80000/-	59 km → elec 488 kms → gas	2 hours
GM Chevyvolt (4 seater)	$37000/-	60 km → elec 500 kms → gas	2 hours.
Porsche Panamera	$113000/-	36 kms	3 hours
Ford Fusion	$38000/-	34 kms	2-3 hours
Ford Cmax	$37000/-	34 kms → elec 557 kms → gasoli.	2-3 hours
Toyota Prius plug-in	$36000/-	18 kms	1-2 hours.

③ Hybrid EV

- HEV have two complementary drive system

A gasoline engine with fuel tank

Electric motor with battery

- Both engine & motor can handle the transmission at the same time & then the transmission turns on the wheels.
- HEVs cannot be recharged from the electrical grids as all their energy comes from gasoline & from regenerative braking.

Advantages	Disadvantages
• Longer range than BEV	• Still produces emission.
• Less gasoline consumption than gasoline only vehicle	• Complex mechanics gasoline + electrical
• less emission than gasoline only vehicle	• expensive to operate (8-10 times expensive than BEV but less than gasoline
	• No easy chargable at homes.

HEV : Audi Q5, Acura ILX, BMW active Hybrid 3,5,7 Honda civic, Hyndai Sonata, Infiniti, Kia Optima, Lexus, Lincoln, Toyota, VW Jetta Turbo.

① **HEV** depending on the drive Train structure (Engine - Motor Connectivity)

- → Parallel HEV
- → Series HEV
- → Combined HEV

② Depending on the share of the electric motor to the traction power

(or)

Degree of Hybrid.

- → Mild (or) Micro hyb (start stop system)
- → Powerassist hyb (series, Parallel or Combined)
- → Full hyb
- → Plug-in Hyb.

③ Depending on the type of nature Power Source (or) non-electrical Source

- → ICE
- → Fuel cell

} Energy Conversion unit. Powered by gasoline, methonal Compressed natural gas hydrogen or other alternative fuels.

- → Hydraullic (or) Pneumatic Power

used with Compressed air; Variable displacement pump replaces motor/gen & hydraulic accumulator replaces battery

- → Human powers & Environmental Power hybrids.

↓ human power combined with further Power Source (eg: Motorized bicycle (water)

Vehicle from on-board solar cell from Grid charged & from Pedals.

Architecture of HEVs :

- HEV is a Combination of the Conventional ICE and EV powered vehicle. It uses both ICE and elec motor/generator for propulsion.
- The two power sources (ICE & motor) Can be connected in series or parallel from the power flow point of view.
- When ICE is Connected in series with the motor, the HEV is a series hybrid in which elec motor provides mechanical Power to the wheels.

- When the ICE is connected in parallel with the motor, the HEV is a parallel hybrid in which both ICE & motor can deliver mechanical power to the wheels.
- In HEV, liquid fuel is the prime source of energy (because of ICE) The elec motor increases the vehicle efficiency & reduces fuel consumption by recoverying Kinetic Energy during regenerative braking & optimizes the operation of ICE during normal driving. Thereby providing extended driving range when compared to Pure EV.
- In Plug-in HEV (PHEV), apart from liquid fuel, electricity is stored in the battery which can be recharged from electric grid. Thereby fuel usage is very well reduced.

- HEVs and PHEVs can also have either series-parallel configuration or a more complex configuration which contains more than one electric motor. These configuration improves the performance of the vehicle and the fuel economy.

Note: In HEVs electric motor provides full torque at low speeds (In traditional vehicles the engine must rampup before full torque can be provided.

- HEV uses with Brushless DC motor, (BLDC) Permanent magnet Syn motor (PMSM) Switched Reluctance Motor (SRM) & AC Induction motor.
- Main advantage of elec motor is that its ability to act as generator (Regenerative braking)

- Maximum operational braking torque is less than the maximum traction torque & there is always a mechanical braking system integrated in the four wheels.
- Accesories like power steering & air conditioners are powered by the electric motor instead of ICE. This allows efficiency gains as accessories can run at a constant speed or can be switched off regardless of the ICE is running. (Example: power steeling saves lot of energy in long haul trucks).

HEV depending on the share of the elec motor to the traction power (degree of hybrid)

Micro Hybrid EV	Mild Hybrid EV	Full Hybrid EV
• Normally operates at low voltages between 12–48V • Power capability less than 5KW & Primarily have auto start-stop functionality • Under braking & idling circumstances, ICE is automatically shut down & fuel economy can improve by 5-10% during city driving condition • Even with 12 V battery some micro HEV regenerative braking also possible.	• Has an independent elec driven train providing 5-20KW of elec propulsion power • Elec drive operates at voltage between 48V-200V • Elec motor assists ICE during the aggressive acceleration needs & also recovers most of the regenerative energy. • This optimizes fuel economy & vehicle performance & improves driving comfort.	• Also called as Strong HEV • The elec drive system normally has in excess of 40KW & operates on a voltage level above 150V. • This elec power train is capable of powering the vehicle for short periods when ICE runs with low efficiency. • Regenerative braking enables the energy storage system to get charged.

• Valve regulated Lead acid batteries like Absorbent Glass Mat (AGM) & gel batteries are widely used. • Micro HEV Cost less • Disadv is that Unable to recover all regenerative braking energy.	• Nickel metal hydride & Lithium ion batteries are used. • Does not have an exclusive electric only propulsion mode. • Fuel saving around 15 to 20%. — x —	• For Special occations (Silent cruising & Zero emission) this can provide pure elec driving range upto 3.2Kms • Ideal for continous stop-and-go operation so widely used for City bus & delivery trucks. • Fuel efficiency upto 40%.

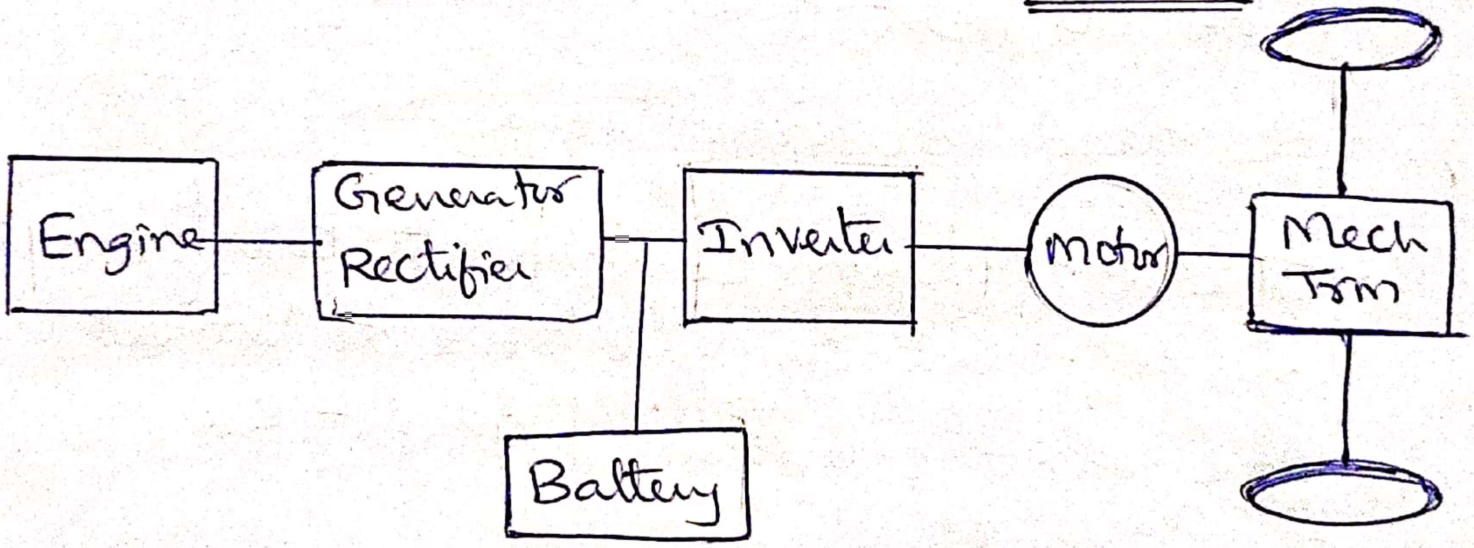
Features & Capabilities ⇓

Type of Vehicle	Start Stop	Regenerative Braking	Boost	only elec mode	elec range(Kms)
Micro HEV	Yes	Possible	NO	NO	NO
Mild HEV	Yes	Yes	Yes	NO	NO
Full HEV	Yes	Yes	Yes	Possible	Possible <3.2Kms
Plugin HEV	Yes	Yes	Yes	Yes	32-96 Kms
Pure	Yes	Yes	Yes	Yes	128-240 Kms

④ Depending on the drive train structure (Engine - motor connectivity) HEV are classified into three types

- Series HEV
- Parallel HEV
- Combined HEV

Series Hybrid Electric Vehicles (SHEV)

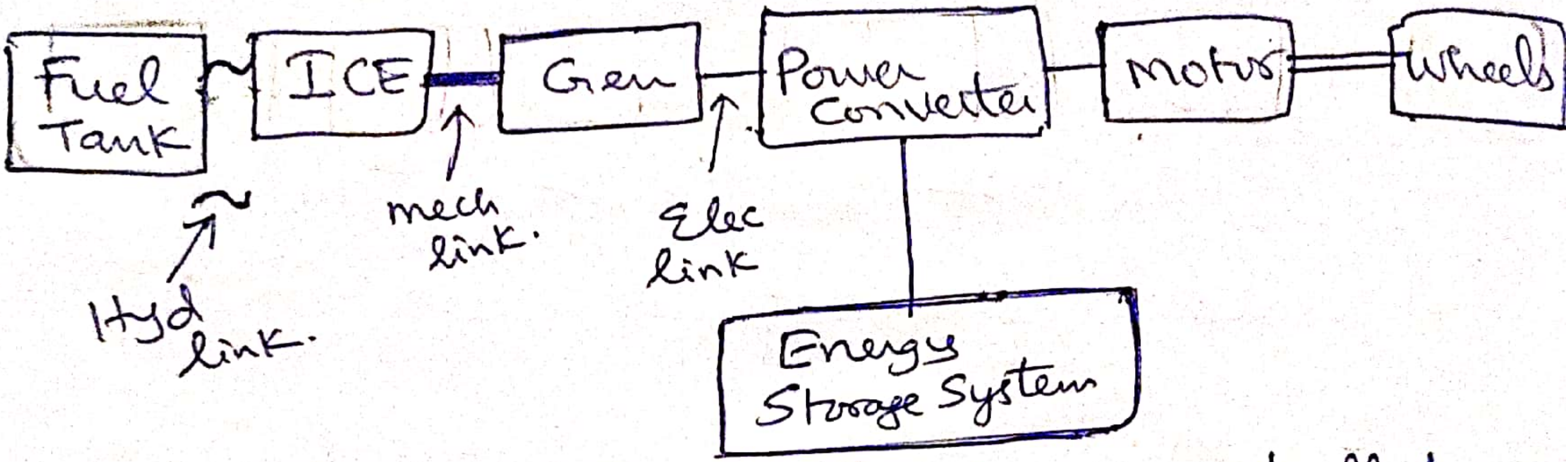


- In this ICE is the main energy source
- The mech energy is converted to electricity using generator.
- The electric motor moves the final drive using the electrical energy generated & the stored battery energy.

- The electric motor can receive elec energy directly from the engine or from the battery or from both.
- As the engine is decoupled from the wheels, the engine speed can be controlled independently irrespective of the vehicle speed so that engine can run at its optimum speed to achieve better/best fuel efficiency.
- No need for traditional mech trm.
- The propulsion components can operate in different combinations to meet out the vehicle operating conditions.
- Engine alone: During highway cruising & at moderate high power demands the ICE/G set is turned on. Battery is neither charged or discharged as the battery's State of Charge (SOC) is at high level.

- **Battery alone** :- when the battery has sufficient energy and the vehicle power demand is low the ICE/G set is turned off & the vehicle is powered by battery alone.
- **Combined Power** :- At high power demands both ICE/G & battery is turned on & supplies power to the elec motor.
- **Power Split** :- when the ICE/G is turned on, the vehicle power demand is below the ICE/G optimum value & the battery's SOC is low then a portion of ICE/G is used to charge the battery.
- **Stationary Charging** :- when the vehicle is not driven (not moving) the power from ICE/G charges the battery.
- **Regenerative Braking** :- when braking is applied the elec motor operates as

generator thereby converting the Vehicle's Kinetic Energy to elec energy to charge the battery.



- Wheel hub motors (one motor installed inside each wheel; Trm & final drive are eliminated so efficiency of the vehicle is increased significantly.

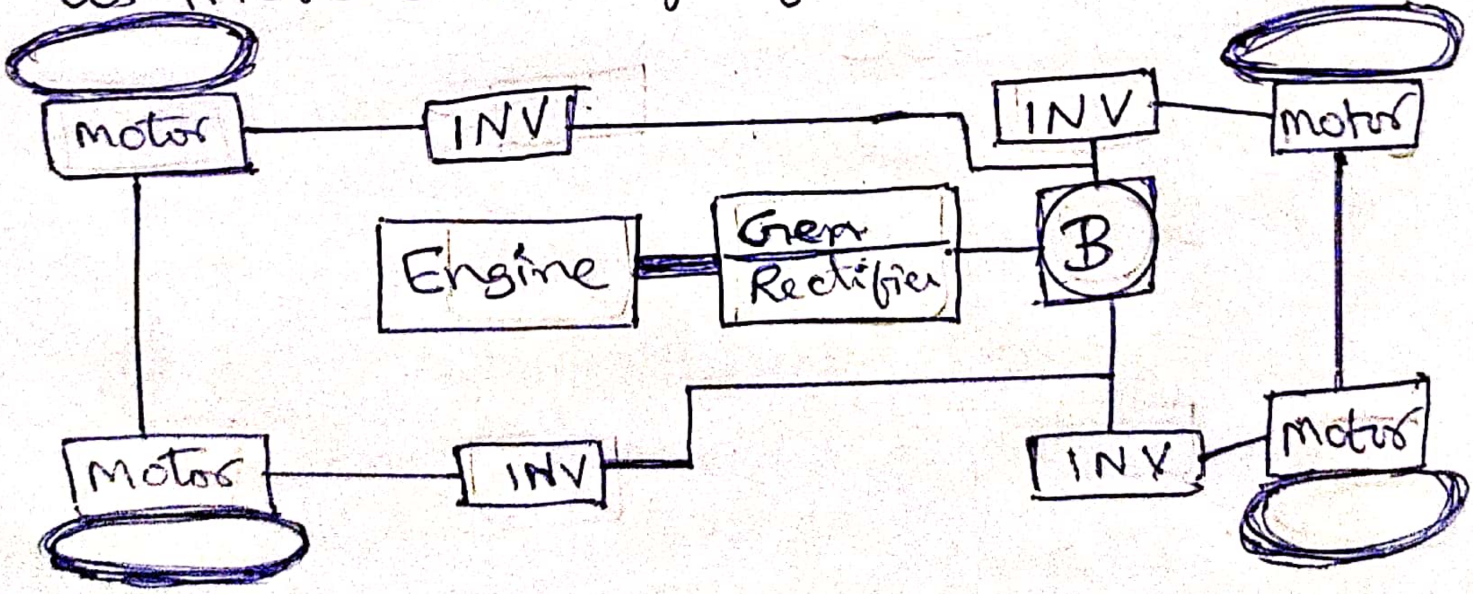


Fig Hub motor in SHEV

▬ Mech link

— electrical link.

INV → Inverter

- The vehicle also have all wheel drive capability but controlling 4 motors will be challanging.

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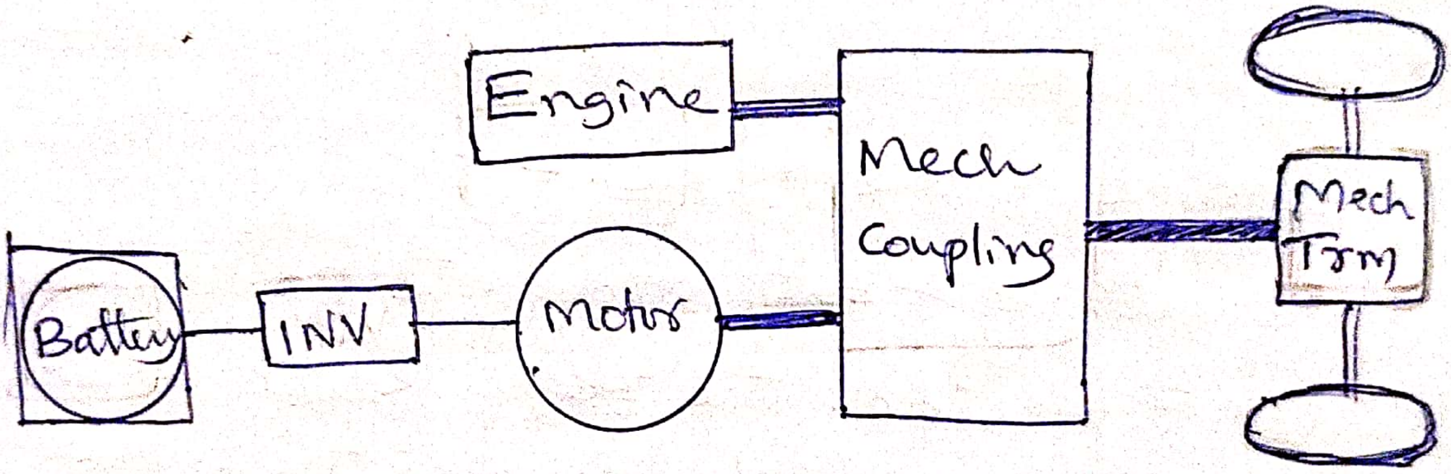
Parallel Hyb Electric Vehicle (PHEV)



- In this ICE and electric motor both can deliver power in parallel to the wheels.
- ICE & elec motor are coupled to the final drive through mechanisms like clutch, belts, pulleys & gears.
- Both ICE & motor can deliver power to the final drive individually or combined.

- Regenerative braking make the motor to act as generator to recover the Kinetic Energy generated or obsorbed i.e a portion of power from ICE.

- This Parallel. HEV (PHEV)s require 2 propulsion system ICE & motors which can be used in the following modes.

- <u>Engine alone mode</u> :- During highway cruising & at moderate power demands ICE provides the required power to drive the vehicle keeping the motor idle. The battery SOC is already in high level & the power demand of the vehicle prevents the engine from turning off or it may not be efficient to turn the engine off.

- Motor alone mode :- If the battery has sufficient backup and vehicle power demand is low then the engine is turned off and the vehicle is powered by the battery & motor only.

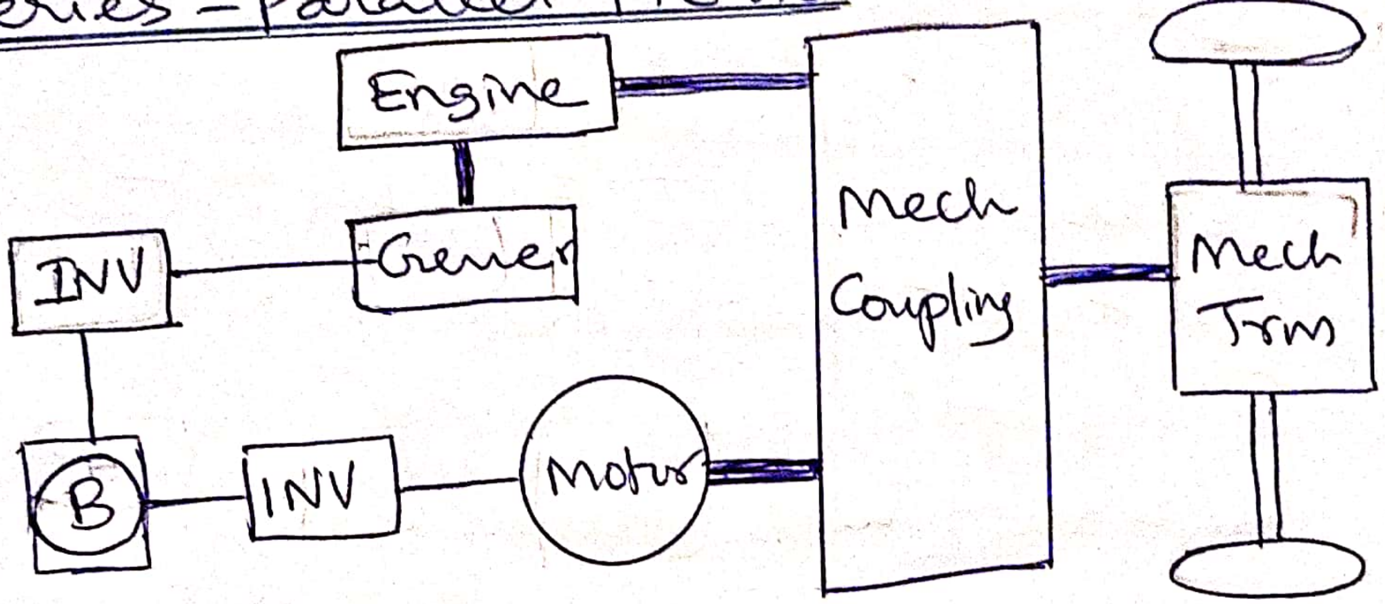
- Combined Power mode :- At high power demand ICE/motor is turned on & both supplies power to the wheels.

- Power split mode :- when the engine is on & the vehicle power demand is low & the battery SOC is low then a portion of power from engine charges the battery.

- Stationary charging mode :- when the vehicle is not running & is on then the running motor acts as generator (also driven by engine) charges the battery.

Regenerative Braking :- Electic motor operates as generator to convert the kinetic energy of the vehicle into electrical energy and charges the battery as the engine is also under operation, addision-al current can also be used to charge the battery by proper controller action.

Series - Parallel HEVs:



- It can be operated as a Series or Parallel HEV
- when compared with Series HEV this adds a mech link between the engine & final drive so the engine can drive the wheel directly.
- when compared with Parallel HEV this adds a second electric motor that serves primarily as generator.

⑤ - As this can operate in both series and parallel modes the fuel efficiency & drivability can be optimized based on the vehicle's operating condition.

- This is a popular choice due to its increased degree of freedom but more components involved makes it more complex & generally more expensive.

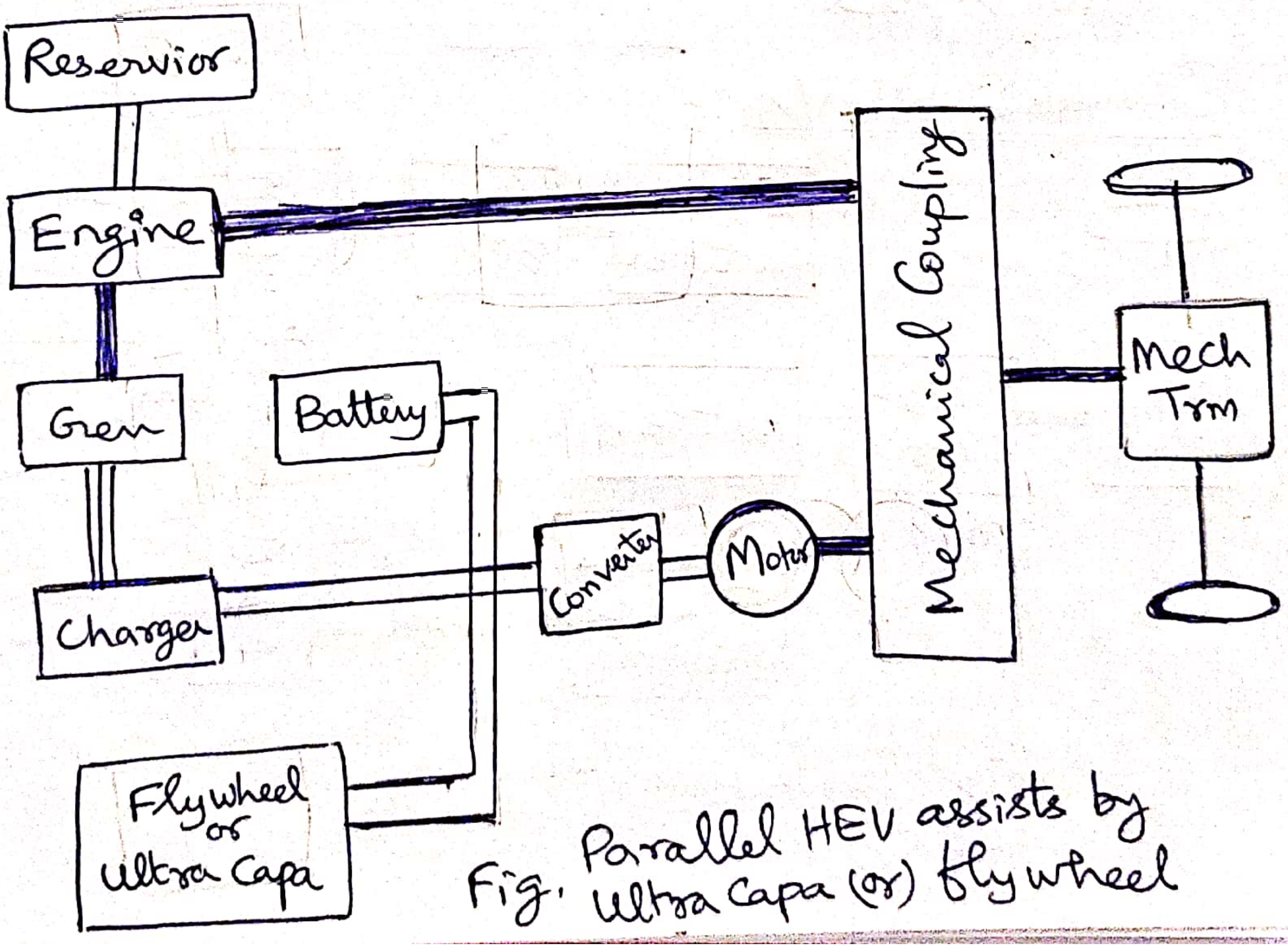


Fig. Parallel HEV assists by Ultra Capa (or) flywheel

- In this PHEV, flywheel or Ultra Capacitor assists the Kinetic Energy ReCooperation System (KERS) to improve the efficiency by minimizing the losses in the battery.
- Ultra Capacitors deliver peak energy during acceleration & take regenerative energy during braking. They are Charged at low speeds & almost empty at top speed.

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Complex HEVs :-

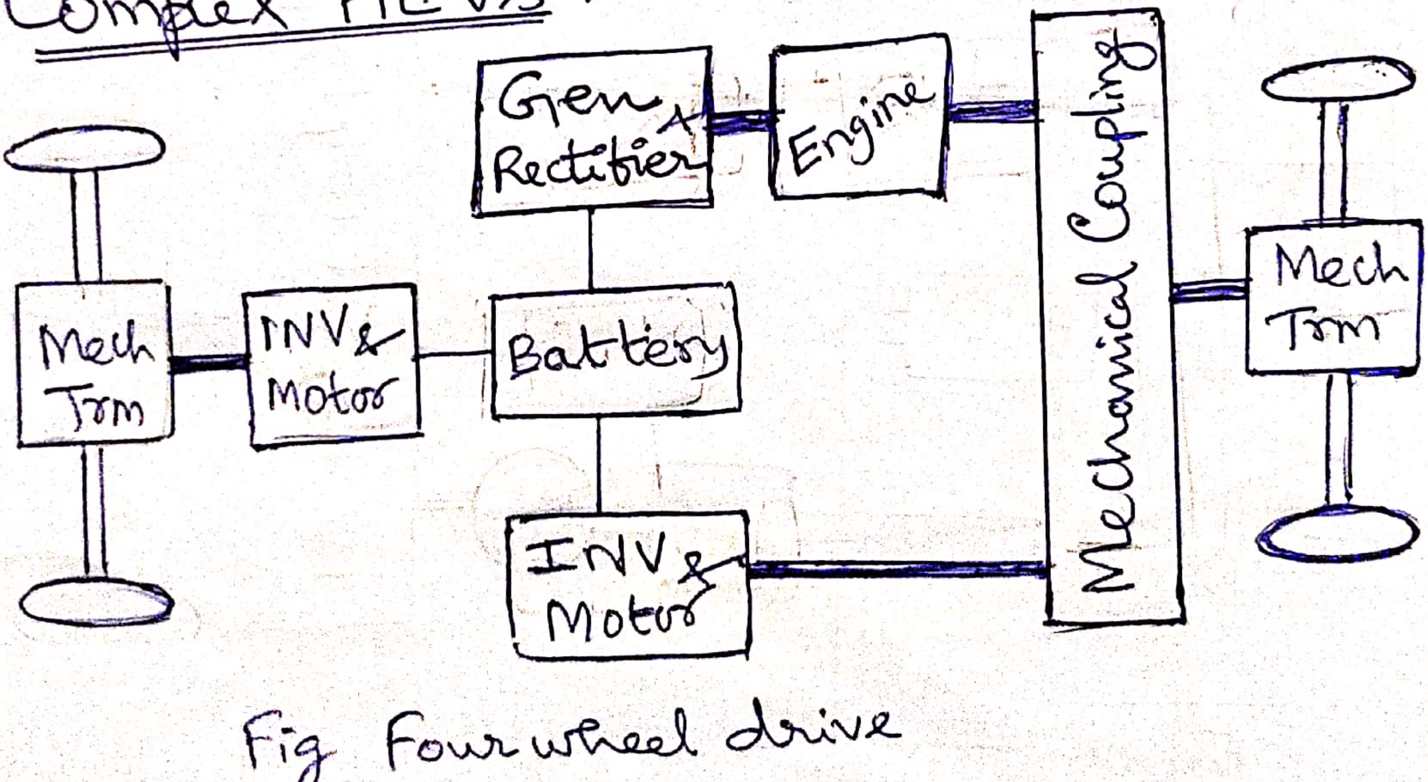


Fig Four wheel drive

- This uses with planetary gear system & multiple electric motors (incase of 4/all wheel drive)
- The Gen in this is used to realize series operation as well as to control the engine operating condition for maximum efficiency.
- Two electric motors are used to realize all wheel drive & to realize better performance in regenerative braking.
- They may also enhance stability control & antilock braking control by their use.

Diesel HEV:

- Similar to the gasoline fed ICE in HEV the diesel fed engine in HEV can be connected in series, parallel or Series- Parallel HEV.
- A Diesel Engine is a reciprocating Piston Engine that automatically ignites the injected fuel through heat during the final stage of compression.
- This type of ignition makes the diesel engine burn fuel at much higher temperature than gasoline engine & so efficiency is high.
- Diesel Engine has longer maintenance interval & lifetime than gasoline engine.
- But Diesel Engine has the disadvantages like noise, Vibration, harshness, Smell

weight, high maintenance cost & an inability to warm up quickly in cold weathers.

- As mentioned earlier the diesel engine have higher fuel economy even in HEV when compared with gasoline fed HEV.
- Hybrid Trucks, Buses can provide significant fuel savings.
- Diesel locomotives are a special type of hybrid. It uses a diesel engine & generator for generating electric power. The electric motor drives the train. This can be referred as Series HEV.
- In some applications without bttey for main drive is being adopted which is called as <u>Simple hybrid</u> when batteries used which can also

be used utilized for short term high current due to torque requirements without restoring to a larger generation.

- Apart from electric-gasoline (or) electric-diesel hybrids compressed air, flywheels & hydraulic systems based HEVs are also available.

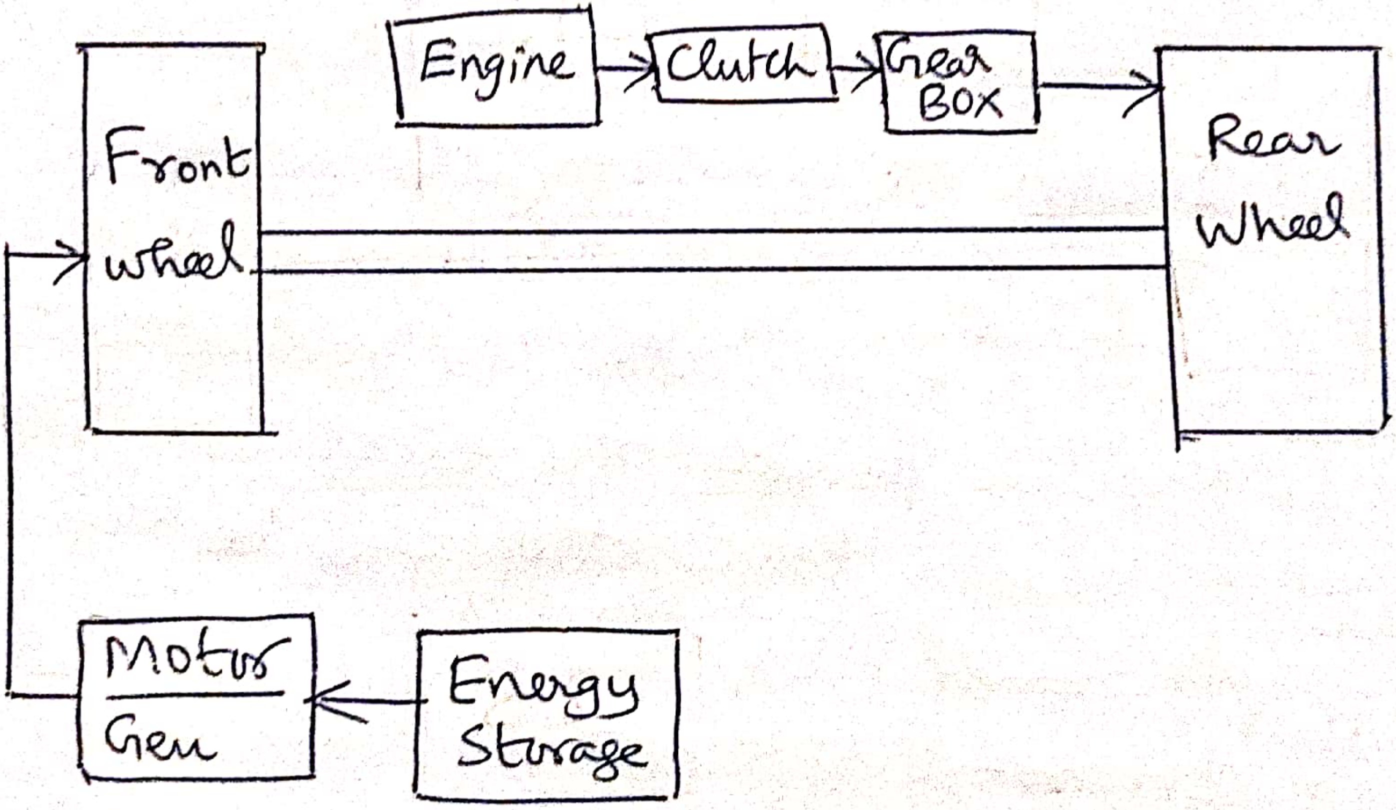
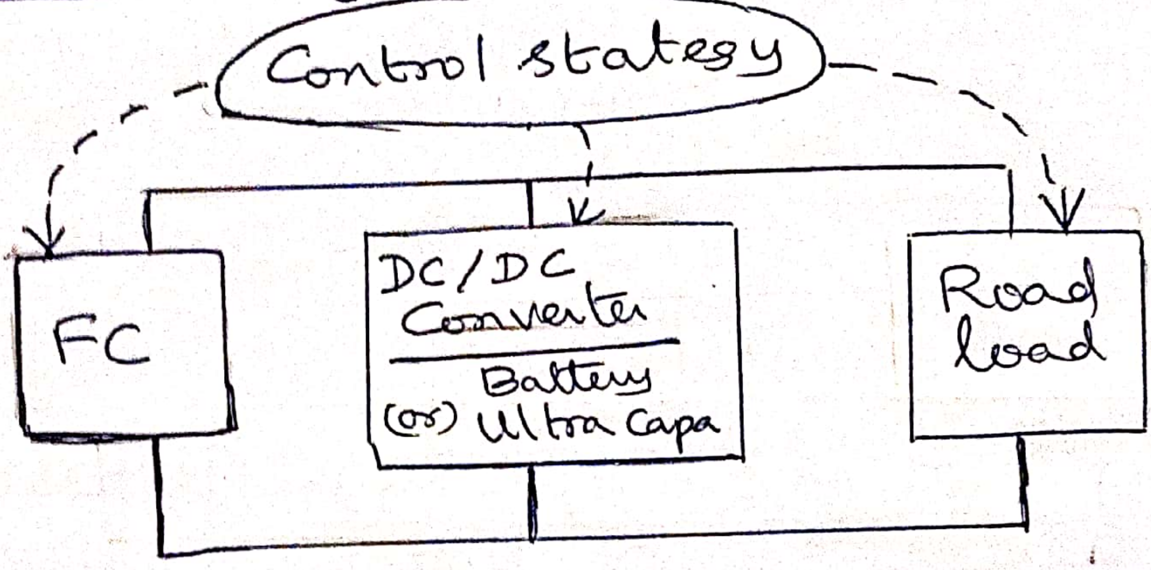


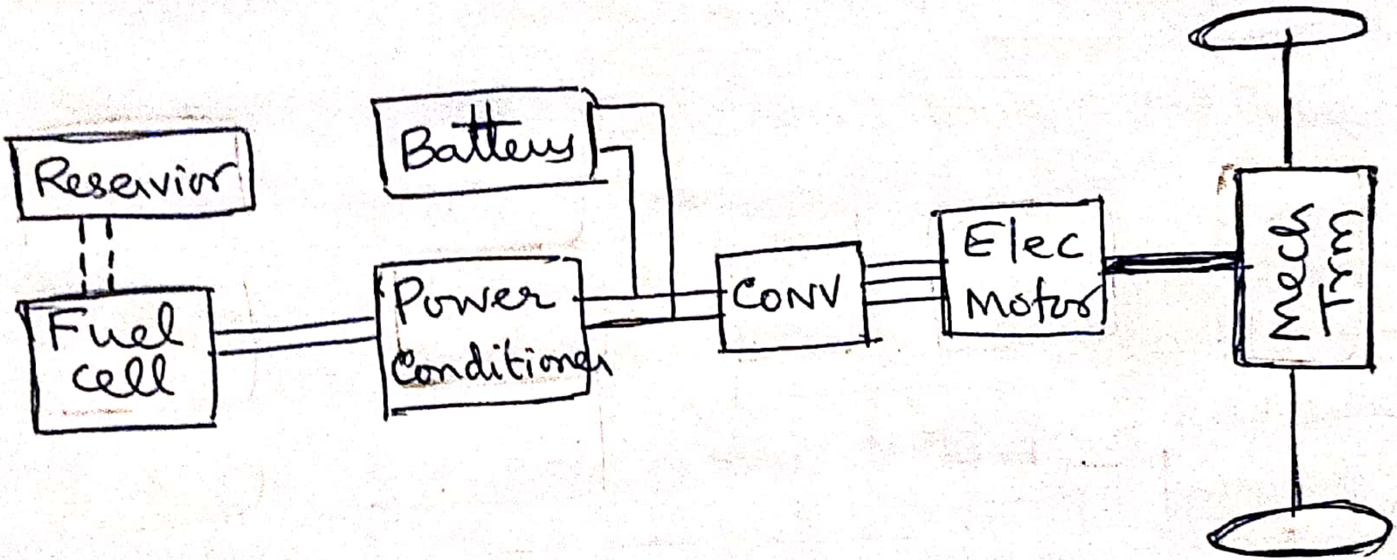
Fig. Parallel HEV PowerTrain

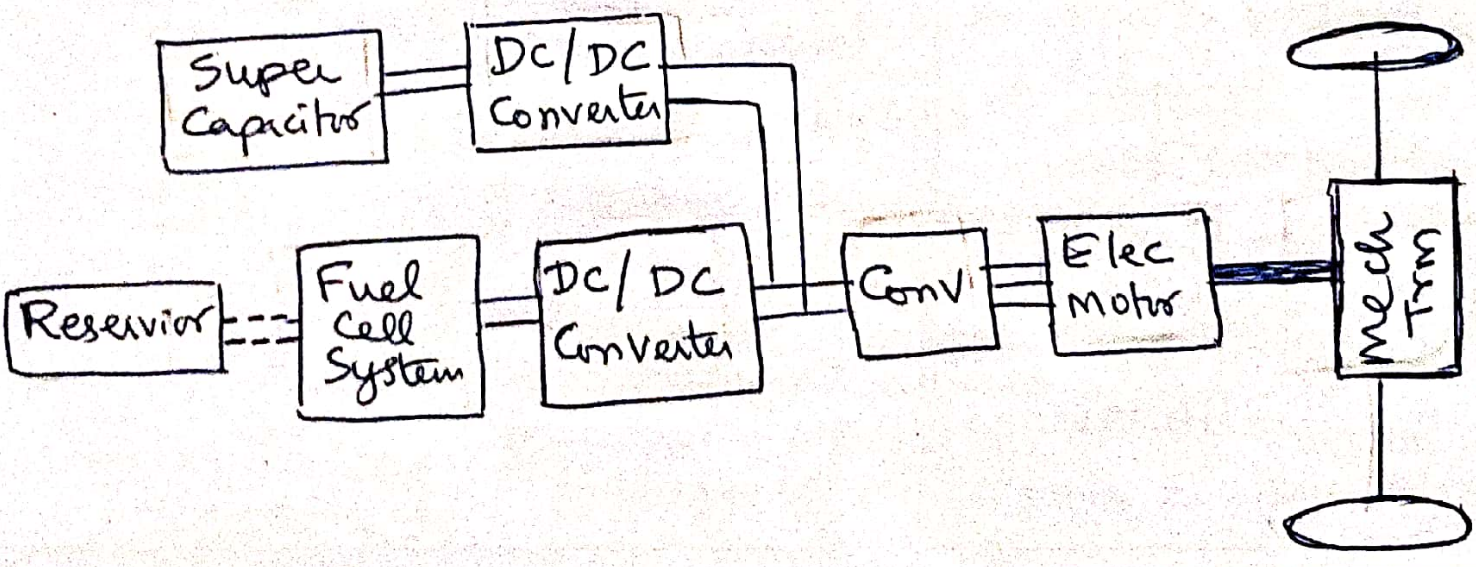
- Based on the location of the gearbox or transmission, Parallel Hybrid Vehicles are Classified as.

Pre-trm Parallel Hybrid Ⓥ	Post-trm Parallel HV	"Through the road" PHV
Engine-Trm-motor • Gearbox located on the main drive-shaft after the torque Coupler so gear Speed ratio applies on both engine & motor so power flow is added at gear box. • Torque from the Motor is added to the torque of the engine at the gear-box input Shaft	• This is also Engine-Trm-motor system • In this the gear-box is located before torque Coupler so the gearbox Speed ratio is applied to engine only. • Here the torque from the motor is added to the torque of the engine at the gearbox output Shaft	• This belongs to Parallel HV. • ICE based Power train Propels one axle & the elec motor Propel other axle (as they are decoupled & it is Simple)

Fuel Cell Hybrid Power Train







⑥ Fuel Cell HEV

- It is a type of Series HV
- Always have series configuration & the Engine/Gen combination is replaced by a fuel cell.

Advantages:

- No mechanical link between ICE & wheels. The engine-gen combinati can also be available.
- No conventional mech trm elements (gearbox, trm shafts etc). Seperate electric wheel motors can be implemented easily.
- ICE can operate (at its most efficient range) in a narrow rpm range even vehicle changes speed.
- Series HV are relatively most efficient during stop & go city driving.

Disadvantages:

- ICE & Motor are used to handle the full power of the vehicle so total weight, cost & size of the power train will be excessive.
- The power from ICE has to run through both gen & Motor.
- As so many energy conversions are available even in long distance highway driving the efficiency is inferieer to Conventinl trm.

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Note

Drive Cycle :- are standard vehicle speed Vs Time profile.
(for testing the vehicle's performance fuel efficiency & emission)

- The required power for operating a Vehicle can be calculated from the driving cycles depending on the mass of the vehicle.

- **Fuel Economy** : Refers to how many miles (or) Kms a vehicle can travel with the Consumption of per unit fuel
- Fuel economy for HEV depends on the driving cycles. Sometimes Composite fuel economy or Combined fuel economy.

Composite fuel Economy
(or)
Combined fuel Economy

$$= \frac{1}{\frac{0.55}{\text{city fuel efficiency Value}} + \frac{0.45}{\text{Highway fuel effici value.}}}$$

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Hybrid Electric Vehicle System Components.

The key Components in Hybrid Vehicles (HV) system when Compared with traditional vehicles are

- Energy Storage Systems (ESS)
- Transmission (Trm) Systems
- Electric Motors.
- Power Electronics related Components.

- **ESS** : This is the most Important subsystem which directly affects the efficiency & other performance factors of the vehicle.

  - This should have high energy density, low internal resistance & long-cycle & calendar life.

Higher Power density battery for traditional HEV

Higher energy density battery for PHEV

- Ultra Capacitor is widely used nowadays which lasts indefinitely & has extremely high charging & discharging rates.
- Because of the above Ultra Capa (UC) provides required surges for accelerating & accumulate charges during regenerative braking.
- UC due to their low energy density & high self discharge rates they are not considered as an energy storage device for PHEV. But when used with higher energy density battery have wide usage.

Transmission (Trm):

- HEV should be able manage ICE driving, electric only driving & combination of the two.
- It has to support start/stop, regenerative braking & shifting the

the operational Zone of ICE & also to match the current requirement by adjusting the parameters.

Electric Motors :

- In hybrid technology efficient, ligent powerful elec motors play a keyrole.
- Elec motor operates in 2 modes

Normal mode (motor exerts constant torque throughout the rated speed range)

Extended mode (when rated speed is exceeded then the motor enters its extended mode in which torque decreases with increase in speed)

- Depending on the architecture of HEV, the motor can be used as peak power regulating device, a load sharing device or a small transient source of torque.

- Motors like DC, brushless DC, AC Induction motors are used based on the design objectives.
- Capturing energy from regenerative braking is also an important task of the elec motor.

- **Power Electronic Components:**
  - DC-DC Converters & DC-AC inverters are the Key Components in HEV.
  - DC-DC Converter converts high voltage supplied by the Energy Storage Systems (ESS) to a low voltage ≃ 12V (head lamps, wipers etc)
  - DC-AC Inverter converts the DC voltage of ESS to a high AC voltage to power the elec propulsion motor. Under regenerative braking the process is reversed and charges the battery.

- The efficiency of these PE Components also have significant impact on the overall efficiency of the vehicle.

Architectures of HEVs.

- HEV is a combination of Conventional ICE powered Vehicle and an Electric vehicle (EV)
- It uses both ICE & elec motor/gen for propulsion.
- These 2 power sources can be Connected in series or in parallel from powerflow point of view.

When ⇒ ICE & Motor Connected in series ⇒ Series HEV in which elec motor Provides mech Power to wheels.

When ⇒ ICE & Motor Connected in Parallel ⇒ Parallel HEV in which elec motor & ICE Provides Mech Power to the wheels

⑦ · In HEV liquid fuel is the source of energy for running ICE. Elec motor increases system efficiency & reduced fuel consumption by recovering Kinetic Energy during regenerative braking & optimizes the operation of ICE by adjusting engine torque & speed during normal driving mode. ICE provides an extended driving range which is far better than pure EV.

- In PHEV apart from liquid fuel, the energy is delivered by battery which can be recharged from electrical grid.
- Actual fuel consumption & emission of ICE driven vehicle can be measured directly. In HEV especially PHEV the elec energy can be calculated from the external source of elec energy (V2G). i-e the elec energy withdrawn

from the source must be seperately accounted for when performing fuel consumption & emission calculations.

- As HEV have multi discipilinary technology so advanced control strategies can significantly improve its performance & lowers its costs.
- The overall control objectives is to maximize the fuel economy & minimum emission.
- The energy flow in the system, availability of energy & power, the temperature of the subsystem & the dynamics of engine & elec motor.

HEV Control Issues:

- ICE should made to work under optimal operating point i.e operates with a good Torque-Speed characteristics

- But ICE at various operating condition is found to be a challenging control objective.

- **Minimize ICE dynamics** :
  - The operating speed of ICE should be kept constant as much as possible & any fast fluctuations should be avoided.

- ICE's fuel efficiency will be low if operated at low speeds.

- ICE speed can be independently controlled with the vehicle speed & can even be shutdown when its speed is below a certain value to achieve maximum benefits.

- The ICE in HEV can be turned off & on frequently (based on the efficiency & emission) as it has a secondary power source.

- The batteries' State of Charge (SOC) be achieves optimally so as to provide sufficient energy to the vehicle.
- Optimal power distribution (ICE + Motor) be ensured based on driving pattern, road + weather conditions as well as the State of ESS not only to maximize the life of ESS but also to achieve the best fuel economy + minimizes the emission.
- Pure Electric mode can be enhanced (in tunnels etc) where zero emission has to be ensured.
- Optimal control of TRM system.

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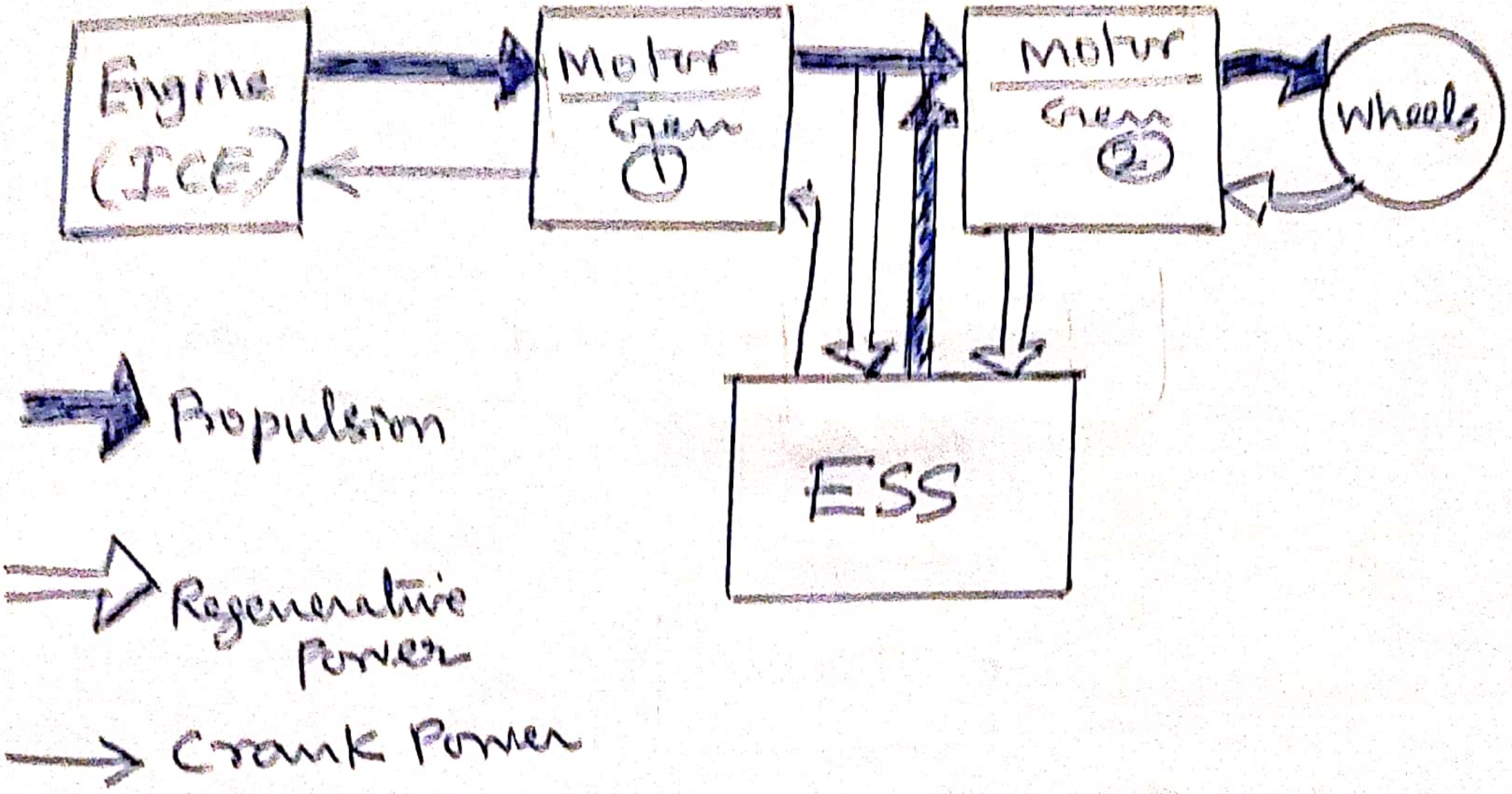
HEV System Analysis

Power flow of HEV

- Different types of HEV Configuration have different power flow paths.



- The engine & gen pair can either power the elec motor or charge ESS
- The propulsion power from elec motor converts the elec energy to mech energy required by the vehicle, while the motor can be powered by either gen or ESS.

- During regenerative braking, the motor works as gen convert mech to elec & charges the ESS.
- When cranking the engine, the battery will provide elec energy to gen.

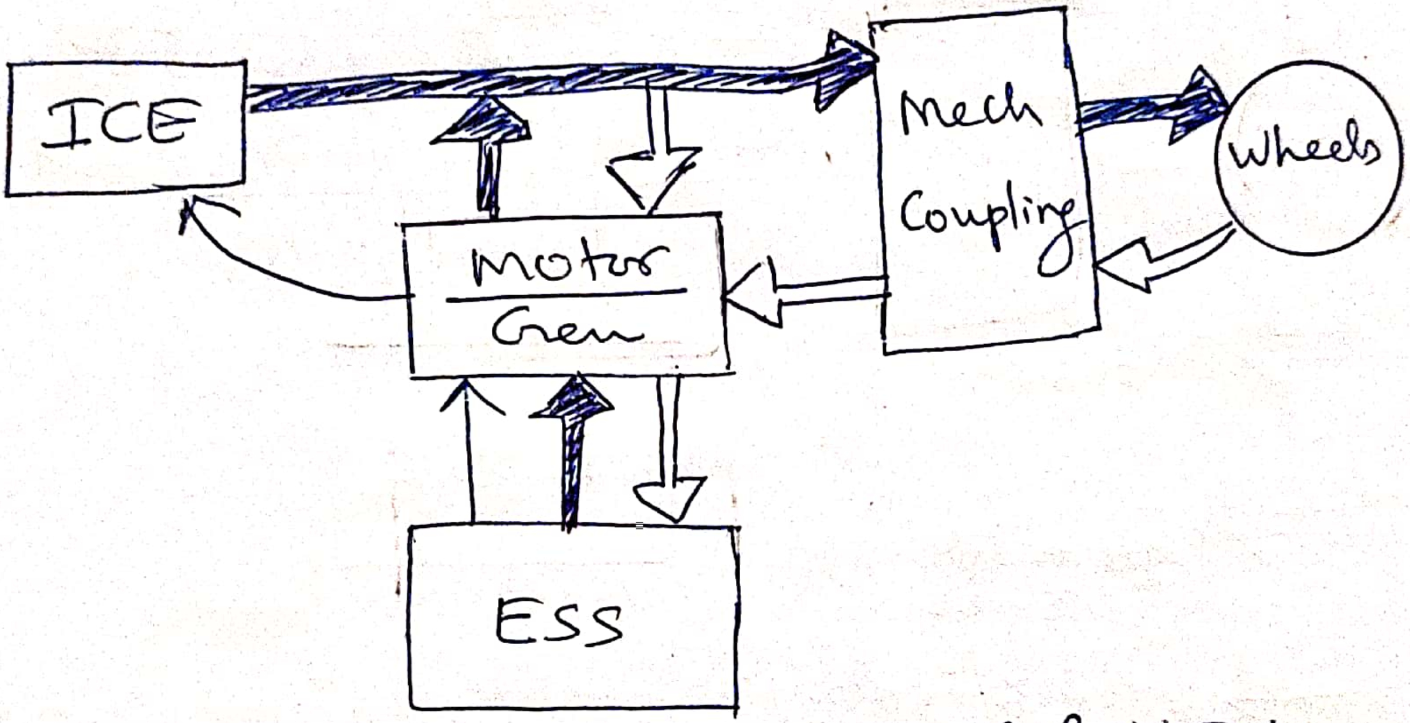


Fig Powerflow in a Parallel HEV.

➡ Propulsion Power.

⇒ Regenerative Power

→ Crank Power.

Cranking the engine simply mean turning the engine's crankshaft that rotates the engine to Power itself.

- In this, the vehicle can be powered with either engine or by motor or by both.
- During regenerative braking the captured braking energy will be converted into electrical energy by the motor & stored in E.S.S.
- The ESS will power motor/gen to crank the engine when the key starts.

Fuel Efficiency Analysis.

- Fuel efficiency (economy) & emission are strongly affected by environmental-factors like driving system, traffic, road condition, weather etc.
- It may not be apt to find fuel economy & emission based on actual consumption & emission measured on the road but Govts & Automobile Industry

have developed series of standard tests to find the fuel Consumption & emission of the vehicle to measure under Completely repeatable Condition & different vehicle Can be Compared fairly to each other. These tests are Called as drive cycle tests & are Conducted routinely for all new Car designs

—— x ——

⑧ For large scale production of HEV, PHEV, Fuel Cell HEV the following points are to be considered.

- Key Technology:
  - Aimed to optimize the fuel economy & reduced emission when compared with conventional vehicle; increased range, reduced charging time, reduced battery size when compared to pure EVs with the advancement of power electronics and electrical machines
- High frequency switching & high power operation of power electronic components & elec motor that generates abundant electromagnetic noise that interfere with the rest of the vehicle system if not dealt properly.

- **Energy Storage System:**
  (ESS)
  - ESS is the major challenge for HEVs & PHEVs;
  - The limitations of present ESS are
    - unsatisfactory power density & energy density.
    - limited life cycle
    - Safety issues
    - high cost
  - Nickel metal hydride batteries for HEV
  - Lithium ion batteries for PHEVs are widely used.
  - When power demand is major concerned in HEV, Ultra Capacitors are used. Flywheels are also used.

- Regenerative Braking Control:
  - Recovering the kinetic energy during braking is a key feature of HEV and PHEVs.
  - But safety & braking performance be ensured with the coordination of the hydraulic/friction braking system with the regenerative braking.
  - optimized vehicle controller be adopted for power management & to achieve better fuel efficieny in a HEV.
  - Power electronic components, elec machines, batteries require a much lower operating temperature than gasoline fed vehicle so a seperate cooling loop is necessary in a HEV

- As in HEV more number of components are involved, modelling & simulation should enable a better vehicle design & associated vehicle dynamics.

- **Cost:**
  - The HEV's and PHEV's cost is significantly more than that of gasoline fed vehicle. So the design should ensure the cost reduction in the selection of various components involved in HEVs & PHEVs

- **Power Generation:**
  - Requires large power generation both from conventional & renewable generations to meet the increased demand of PHEV & also for rapid & convenient charging of PHEVs from grids.

- **Integrated Approach:**
  - An integrated approach that Combine high efficient engine, vehicle safety & smart roads will help Consumers using HEV & PHEVs.

—x—

UNIT III Electric Trains

① Electric Drive-Trains - Basic Concepts of electric traction - Introduction to Various electrica drives train topologies, powerflow control in elec drive train topologies, fuel efficiency analysis.

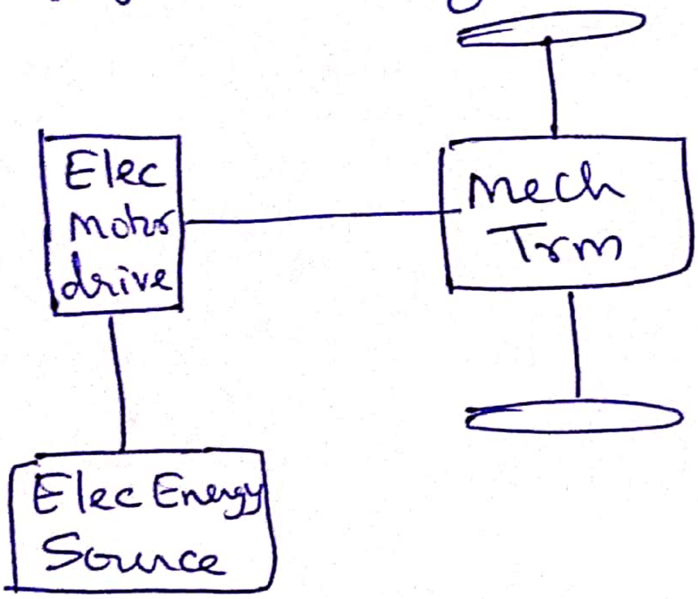
Electrical propulsion unit - Introduction to elec components used in Hyb. Elec Vehicles Configuration & Control of DC motor drives, Induction motor, Permanent Magnet Motor drives, & Switch Reluctance motor drives, drive system efficiency. —

Electric Vehicle (EV) use, an electric motor for traction & chemical batteries, fuel cell ultra capacitor and/or flywheels for their corresponding energy sources.

EV has:

absence of emission, high efficiency, Independent from petrolium, Quite & Smooth Operation.

Configuration of EV



Disadv of EV : heavy weight, lower flexibi-lity & performance degration.

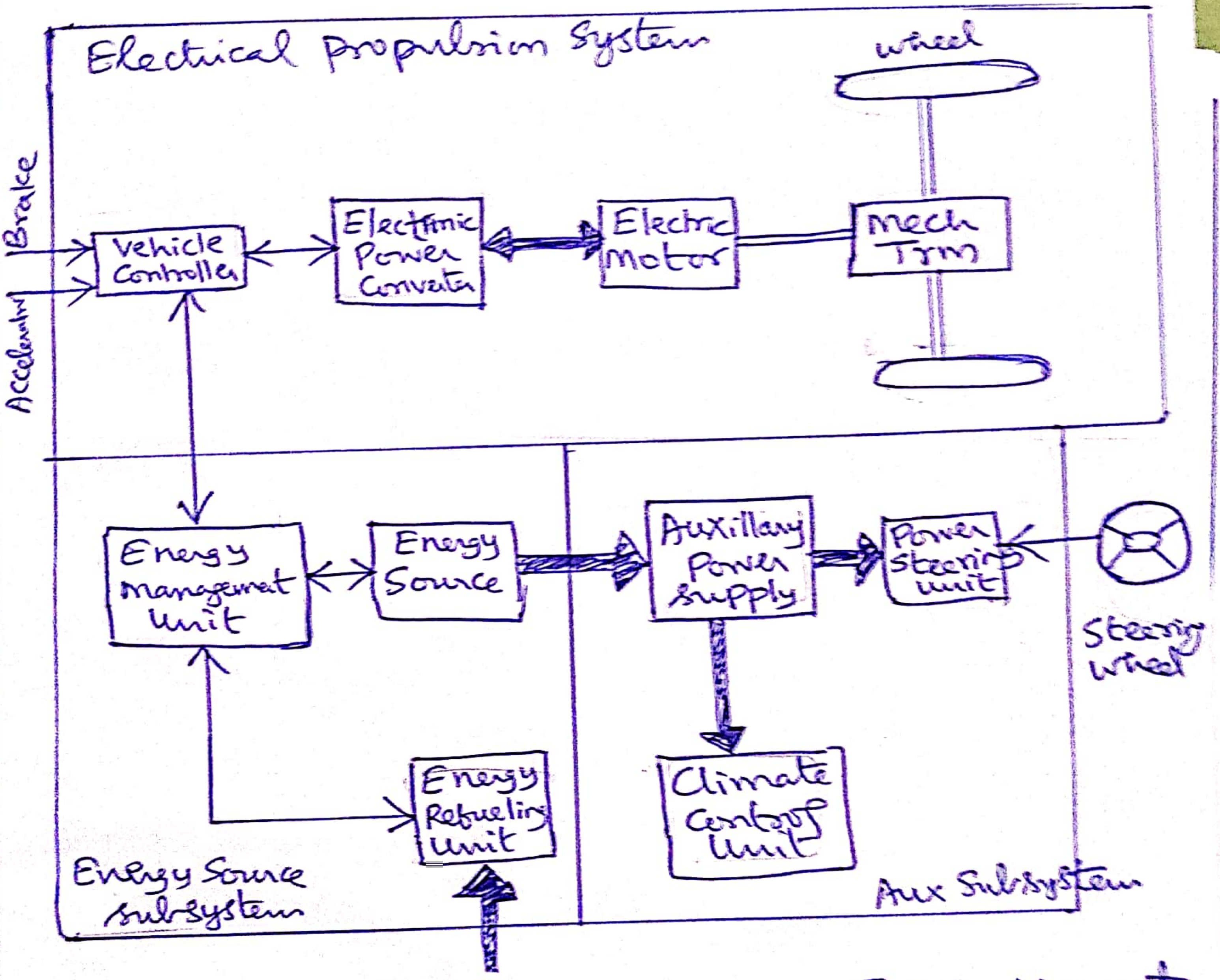
Modern Electric drive train :

The drive train has 3 major subsystems

① Elec motor propulsion sub system → Vehicle Controller, Power Electronic Converter, Elec motor, Mech Trm.

② Energy Source sub system → Energy Source, Energy management system, Refueling Unit

③ Auxillary Sub System → Power Steering Unit, Aux. power supply, Climate Control unit

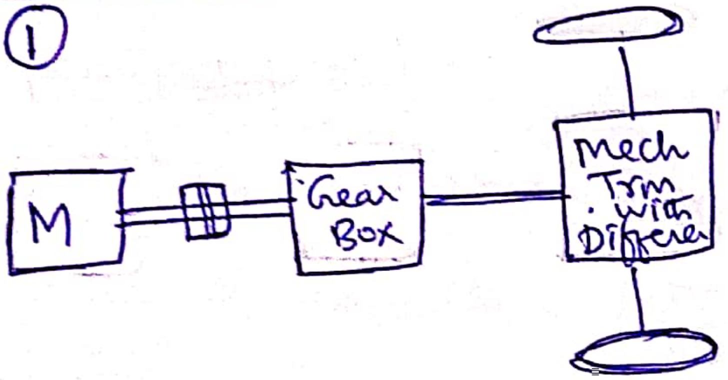


Conceptual Illustration of EV Configuration

- Based on the Control input from accelerator & brake pedals, the vehicle Controller Provides proper Control Signal to the Power Electronic Converters to regulate the power flow between elec motor & energy source.
- Regenerative braking of EV Can be used to charge the Energy storage
- Most of the EV batteries as well as Ultra Capacitors & flywheel posses the ability to accept the regenerative braking power.
- The energy management Coordinates with the vehicle Controller to Control the regenerative braking & its energy recovery.
- It also works with energy refueling unit to Control the refueling Unit & monitors the usability of the energy sources.

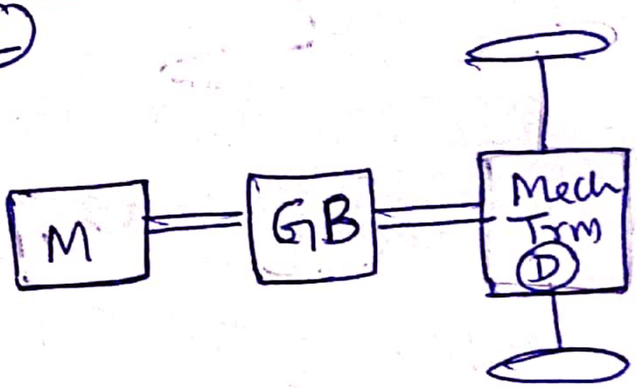
- <u>Auxillary Power Supply</u> provides the necessary power at different voltage levels for all the EV auxillaries, especially the vehicle climate control & power steering units.

①



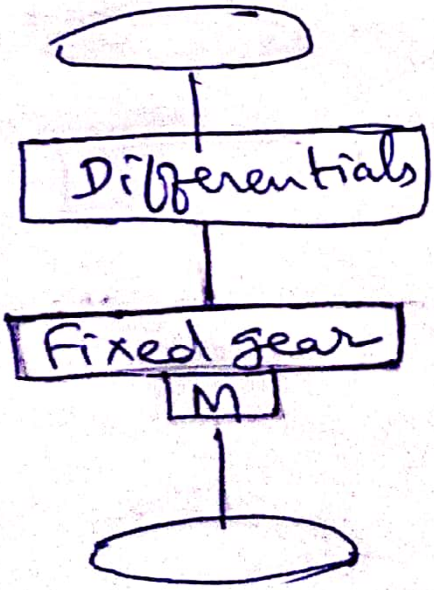
Motor, clutch, gearbox differentials (or) Automatic Transmission

②



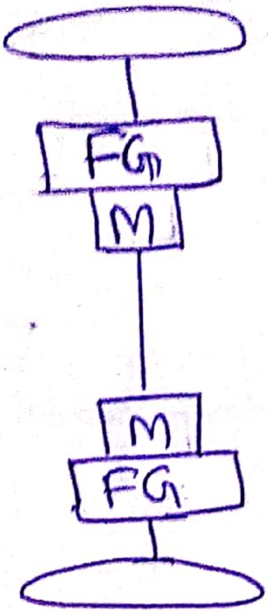
When an elec motor has a constant power in a long speed range, a fixed gearing can ~~be~~ replace the multi speed gearbox & reduce the need for a clutch.

③



Similar to train in ② Motor (M), fixed gear & differential can be further integrated into a single assembly while both axles point at both driving wheels. The whole drive train can be simplified & compacted.

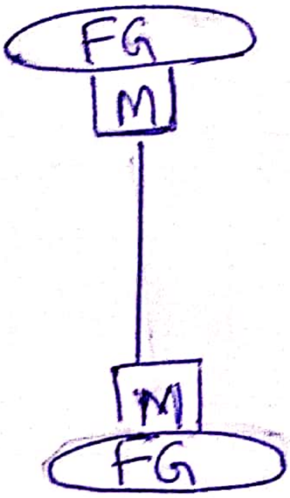
④



Mechanical differential is replaced by two traction motors.

Each of them drives one side wheel & operates at a different speed when the vehicle running in curved path.

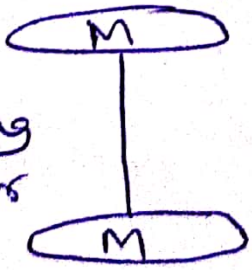
⑤



To further simplyfy the driving train the traction motor is placed inside the wheel (called as in-wheel drive).

A thin planetary gearset may be used to reduce the motor speed & to enhance the motor torque. This planetary gear performs high speed reduction ratio as well as an inline arrangement of I/p & O/p shafts

⑥



No mech gearing between elec motor & driving wheel.

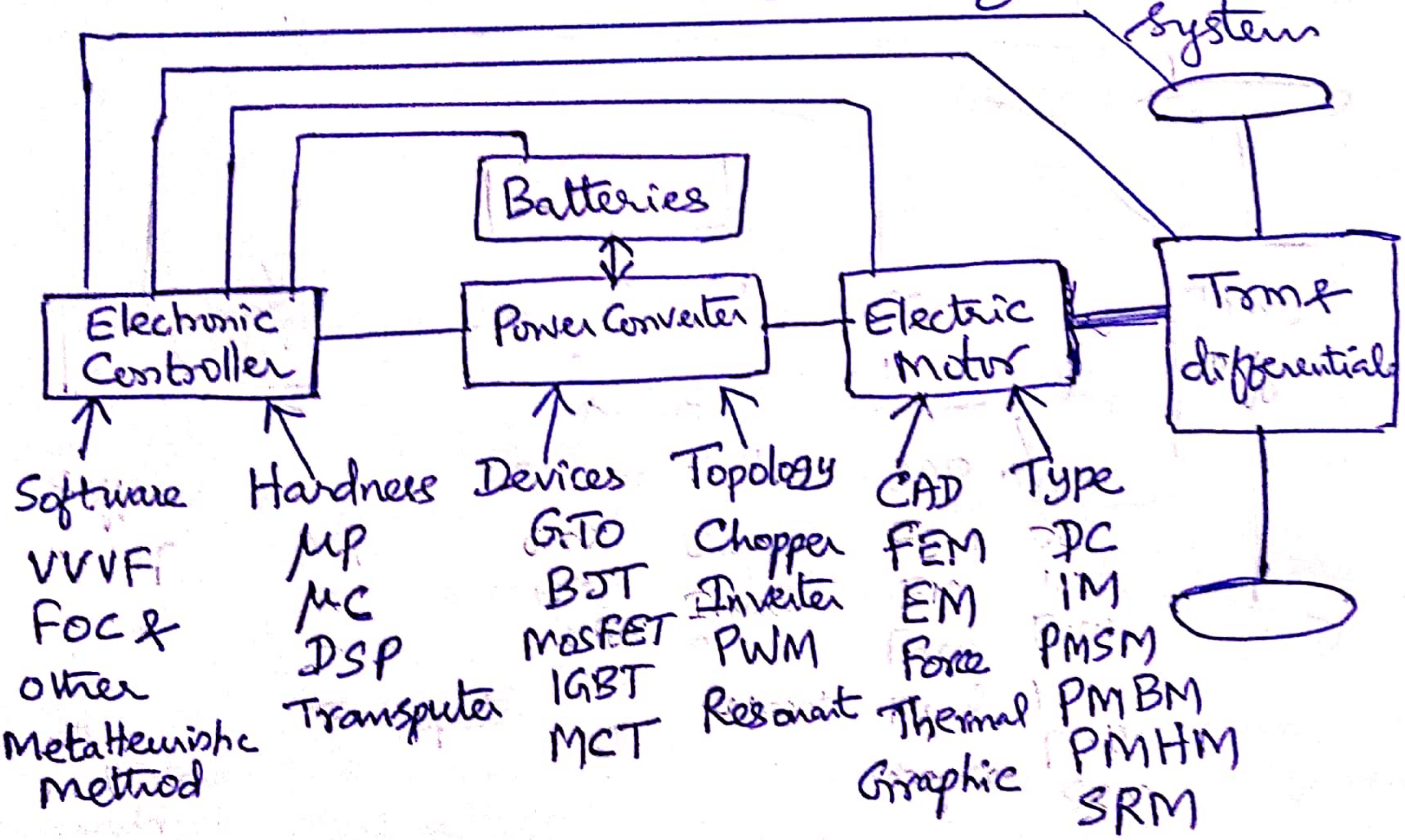
Have in-wheel driving mechanism.

Motor directly connected to the driving wheel.

The speed control of elec motor is the control of wheel speed

This requires to have high torque for starting & accelerating.

Functional block diagram of EV propulsion system



Elec propulsion can be divided into two Parts

Electrical

Consists of subsystems like motor, power converter & Electronic Controller

Sensors — translates the measurable quantities like Voltage, Current, Temperature

Interface circuits

Processor (output signals are amplified via interfacing ckts)

Mechanical

Consists of subsystems like mech trm (optional) & vehicle wheels.

speed, torque, flux
to electronic signals.

- The Converter acts as power conditioner that regulates the powerflow between energy source & motor for motoring & regeneration

- The Choice of elec propulsion system in EV mainly depends on

driver expectation
- acceleration
- Max speed
- Climbing capabilities
- braking & range

Vehicle
Constraints
- depends on
vehicle type
vehicle weight
& primary load

Energy
source
depends
on Fuelcell
capacitors
Flywheels
&
hybrid
sources.

Concept of EV motors

- This usually requires frequent start/stop high rate of acceleration/deceleration, high-torque low speed, hill climbing low-torque high-speed Cruising & very wide-speed range of operation.

EV motors	Industrial motors
Need to offer maximum torque that is 4 to 5 times the rated torque for temporary accelerati- & hill Climbing.	maximum torque that is twice of rated torque for over load operation
Need to achieve 4 to 5 times the base speed for highway cruising.	achieve upto twice the base speed for Constant power operation
Designed for vehicle driving profiles & driver's habits	usually based on a typical working mode.
Demand both high power density & high effic over wide speed - torque ranges for a reduction of total vehicle weight & exten-sion of driving range.	Generally need a compromise among power density, efficien & cost with the efficiency optimized at the rated operating point
Desired to have high Controllability, high	only special purpose desire the same

② EV motors	Industrial motors
Steady State accuracy & good dynamic performance for multiple motor Coordination.	
Installed in moving vehicle with harsh operating Conditions like high temperature frequent Vibration, bad weather Conditions	Located in a fixed place.

- From Technological point of View EV usage can be classified as single & multiple motor Configuration.

① Single motor Configuration

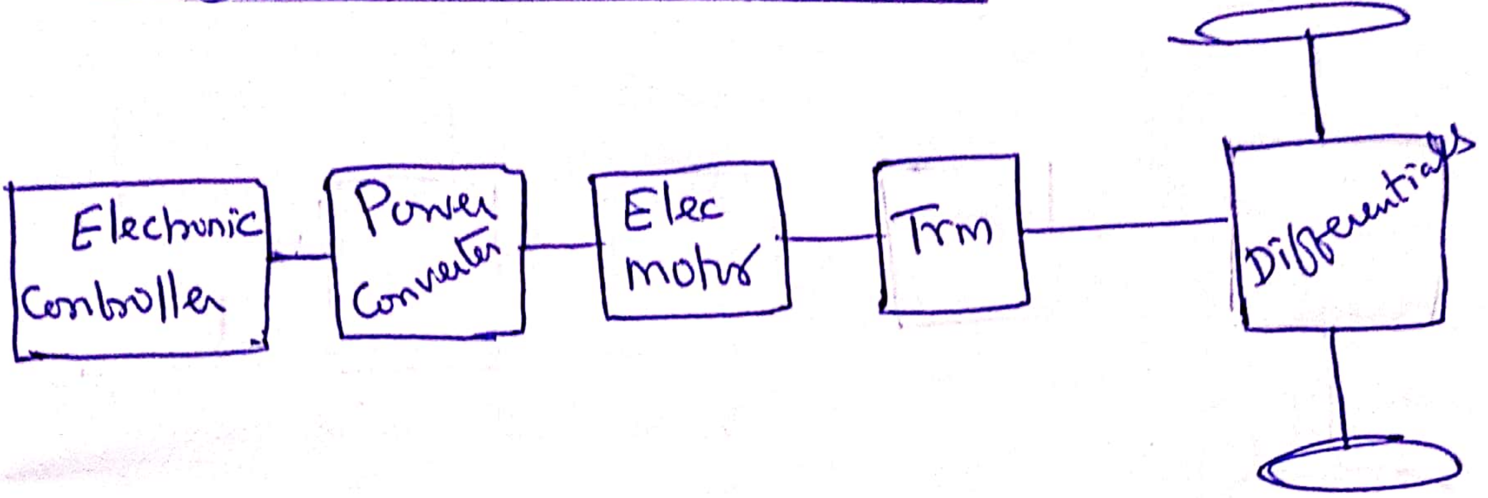
As the name implies this adopts one motor to propel the driving wheels which can minimize the size, weight & cost.

(2)
Multiple motor configuration:

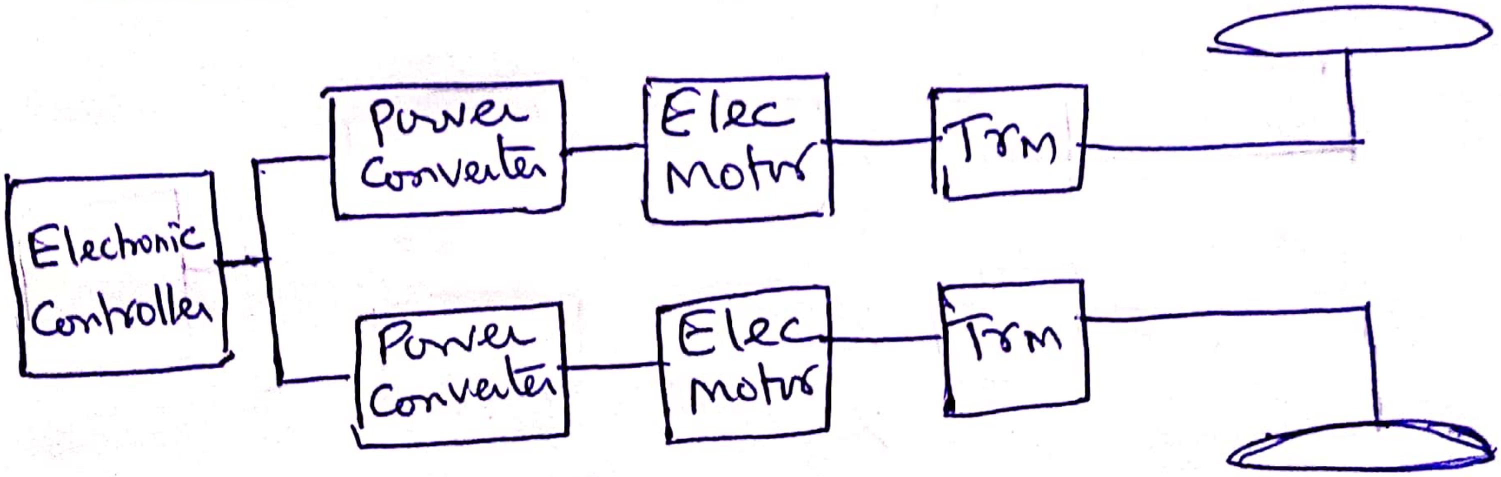
- Multiple motors permanently coupled to individual driving wheels.
- This has the advantages of having reduced current & power ratings of individual motors & evenly distribute the total motor size & weight.
- In this addisional precaution requires in allowing fault tolerance during electronic differential actions.
- Each motor may have its own controller which is controlled by a centralized controller. (Master Controller)

	Single motor	Dual motor
Cost	low	high
Size	Lumped	Distributed
Weight	Lumped	Distributed
Efficiency	Low	high
Differential	Mechanical	Electronic

Single Motor Configuration :



Dual Motor Configuration



② Fixed or Variable gearing Trm.

Single speed (Fixed gearing)

As fixed gear alone available it should provide both high

multiple speed Trm.

(with gearbox & clutch

- In this geared trm is available.
- The Conventional Motor achieves high starting torq

instantaneous torque (3 to 5 times rated Value) in the Constant torque region & high operating speed (3 to 5 times the base speed) in the constant power region. at low gear & high cruising speed at high gear.

- This Variable gear has the drawback of having heavy weight, bulky size, high cost, less reliable & more Complex.

Comparision of fixed & Variable gear Trm.

	Fixed gearing	Variable gearing.
Motor rating	high	low
Inverter rating	high	low
Cost	low.	high.
Size	small	large
Weight	low	high
Efficiency	high	low
Reliability	high	low.

Geared (or) Gearless

- The fixed speed gearing with a high gear ratio makes the EV for high speed operation resulting high power density.
- The maximum speed is limited by friction windage losses as well as transaxle tolerance.
- EV motor can act without using gears results in the use of low speed outer rotor-motors which suffers from relatively lower power density.
- With the advent of compact planetary gearing, the use of high speed planetary geared in-wheel motors are becoming more attractive than the use of low-speed gearless in-wheel motors.

Integration: The EV motor design should concentrate more on the characteristics of the motor with Converter, Controller, trm, & energy sources before integrating these Components.

System Voltage:

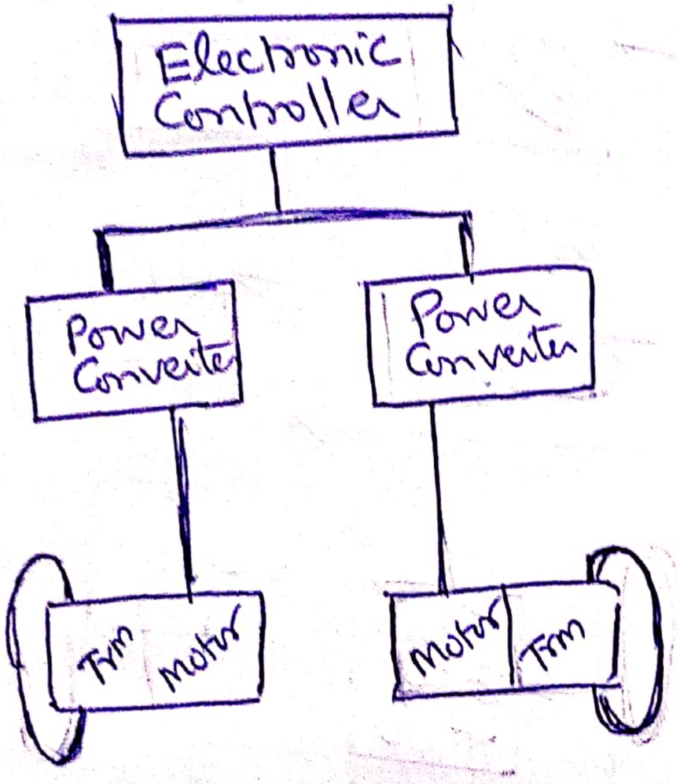
- Reasonable desired high voltage motor design Can be adopted to reduce the Cost & size of the inverters.
- If the desired voltage is too high, a large number of batteries have to be connected in series results in reduction of interior & luggage space, the increase in vehicle weight & cost and also the degredation of the vehicle performances.
- The system Voltage is governed by the the battery weight which is about 30% of the Vehicle weight
- In general, high Power motors adopt high Voltage levels.

example:

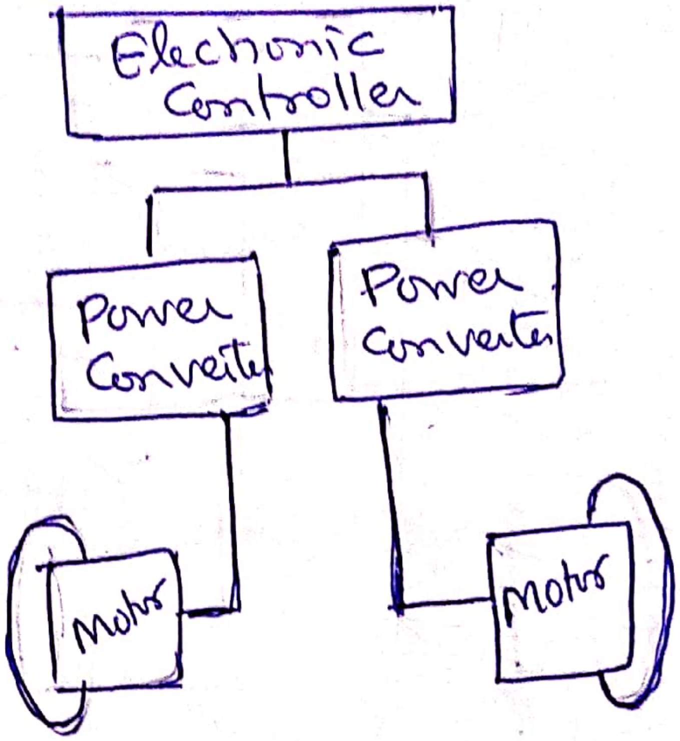
GM EV adopts 312V for its 102 kw motor.

Reva EV adopts 48V for its 13 kw motor.

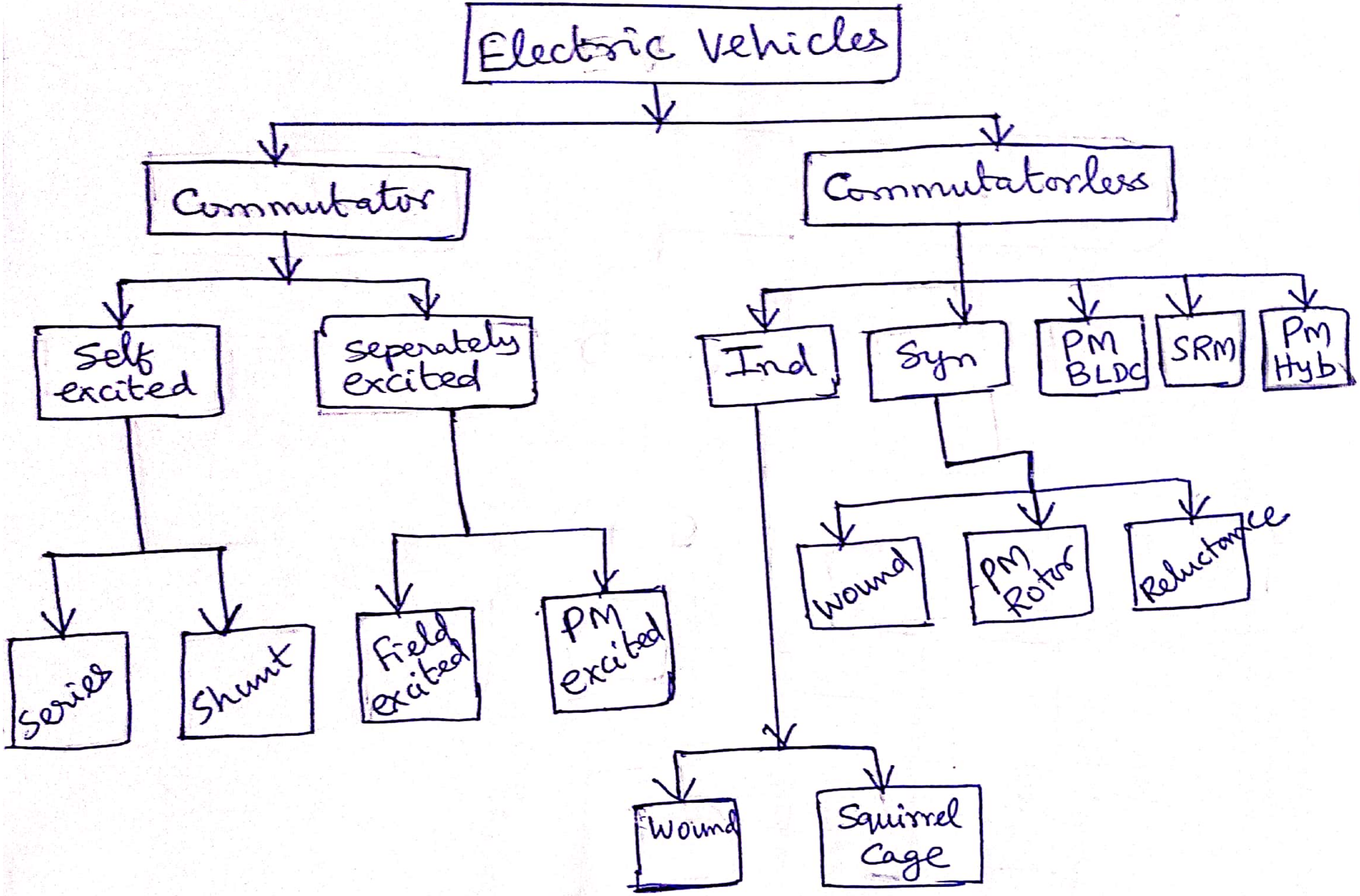
Geared EV



Gearless EV



Classification of EV motors.

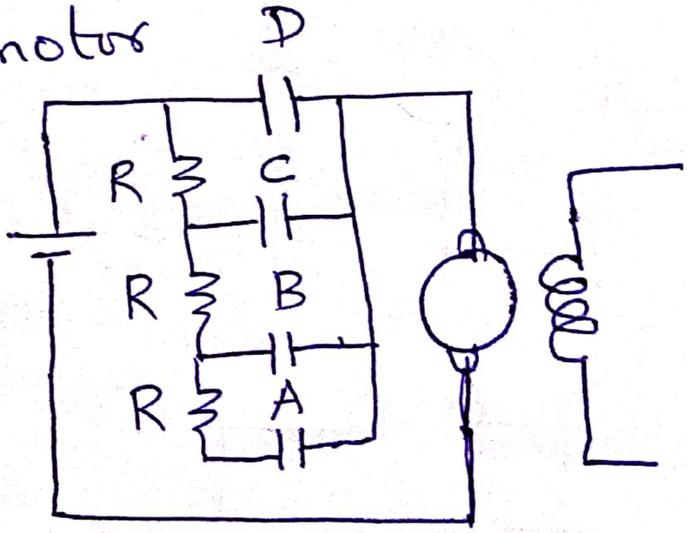


Configuration & Control

③ DC Motor drive.

- Wound field (has field winding & can be controlled by dc current)
- Permanent Magnet (no field wdg & PM field is uncontrollable)

- Earlier DC motor drives consisted of a string of resistors connected in series and/or in Parallel with the dc motor



- Motor voltage can be increased by operating contactors to shortout a portion of a resistance

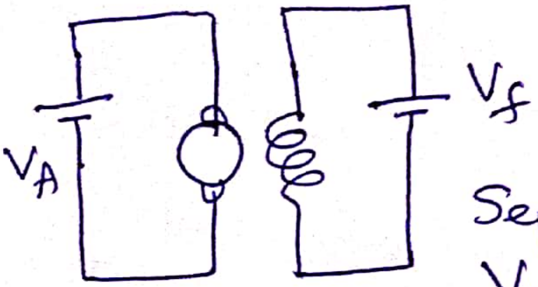
ABCD are extremely controlled contractors.

Although simple & cheaper it has poor efficiency; Considerable energy waste as heat & smooth control not possible.

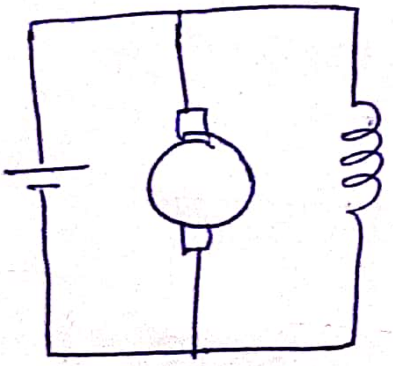
Motor voltage = Battery voltage − drop across resistors

- With the Power electronics development basic one-quadrant dc chopper for speed control of dc motor drives.

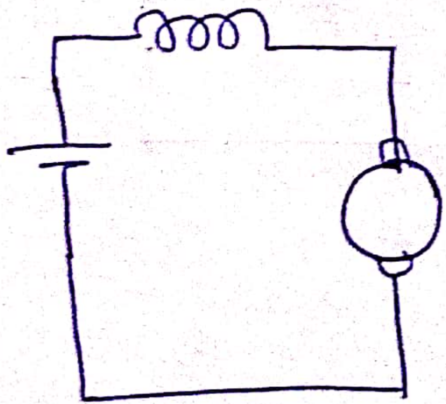
lessweight, small size
highefficic,
high controllability



Seperately Excited
V_f, V_A can be controlled independently

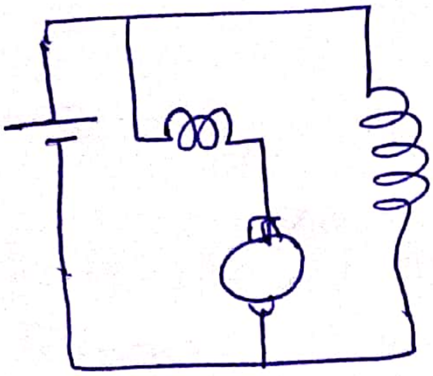


Shunt Motor.
field and armature connected to common voltage source.



Series Motor
$I_a = I_f$.

$$\left.\begin{array}{l} V_a = E + R_a I_a \,;\ E = K_e \phi \omega_m \\ T = K_e \phi I_a \,; \end{array}\right\} \Rightarrow \text{from this eqns } T = \frac{K_e\phi}{R_a} V - \frac{(K_e\phi)^2}{R_a} \omega_m$$

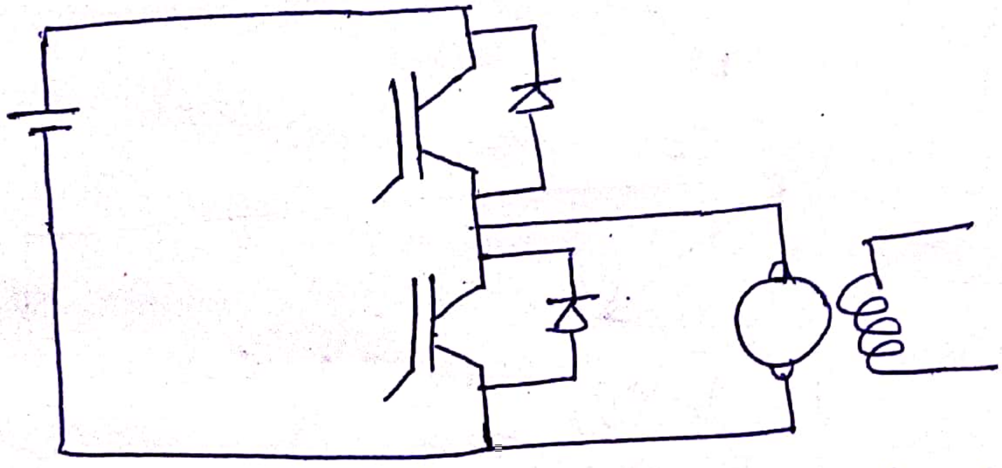


Cummulatively Compound.

mmf of series field in same direction of shunt field.
(lies between series & shunt motor)

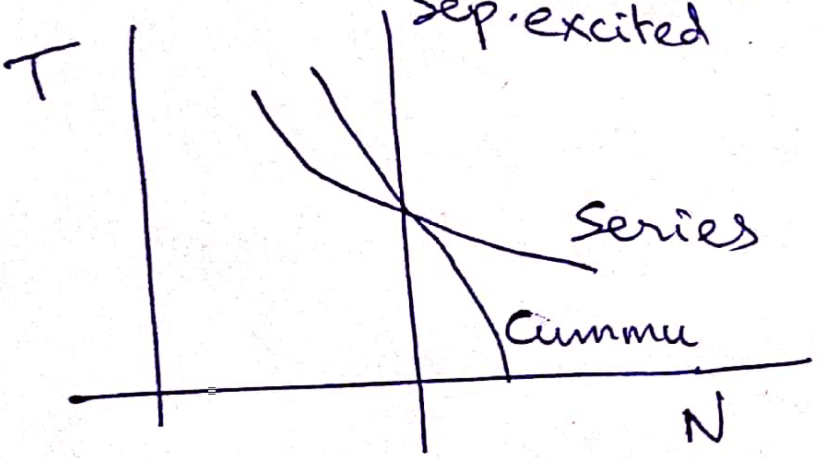
Fig: Wound field dc motor.

Two Quadrant dc Choppers for EV propulsion



When dc-dc converter adopts a chopping mode of operation, they are usually termed as dc choppers & are extremly/extensively used for voltage control of dc motor. drive,

DC Choppers
- → First quadrent (Suitable for monitoring & Powerflow from source to load)
- → Second quadrent (Suitable for regenerative & powerflow from load to source)
- → 2 & 4 quadrant versions



Chopper voltage can be varied

- PWM
  Chopper frequency is kept constant & pulse width Varied
- Frequency modulated Control.
  Constant pulse width & Variable frequency → Chopping.
- Current limit Control
  Both Pulse width & frequency are Varied to Control the load current between Certain specified max & min limits

- For Conventional DC motor drives for EV PWM control of 2 quadrant dc Chopper is generally adopted.
- Soft switching dc-dc Converter are seldom used for Voltage Control of dc motor drives due to the fact that the corresponding development has been much lesser than that of switched mode power supplies & also they cannot handle the regenerative power developed during braking.

Speed Control : by Armature Control &
field Control

$V_A \downarrow$, $I_A \downarrow$ Torque ↓ causing Motor Speed ↓

& $V_A \uparrow$ Torque ↑ causing motor speed ↑

Since maximum allowable I_a remains Constant & the field is fixed this armature Voltage Control has the advantage of retaining the maximum torque Capability at all speeds. As the Va cannot be further increased beyond rate value this Control is used when the motor drive operates below its base speed.

- But when V_f is weakened while Va is fixed the motor induced emf decreases. Because of low armature resistance, Ia ↑ much larger than the decrease in field then Torque ↑ causing motor speed ↑. Since the max allowable Ia is Constant, the induced emf remains constant for all speeds when V_a is fixed. so the max allowable P_a (motor Power) is Constant. So that the max allowable torque Varies inversely with the motor speed. So inorder to have wide-range Speed Control in dc motor drive for EV armature Control has to be Combined with field Control.

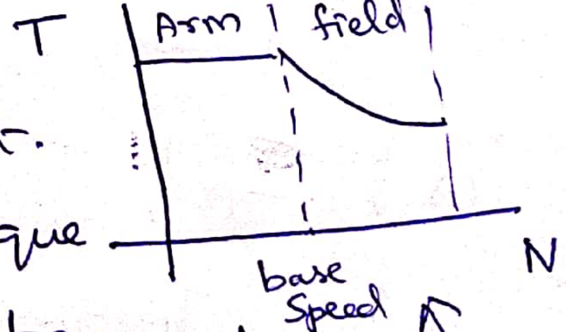
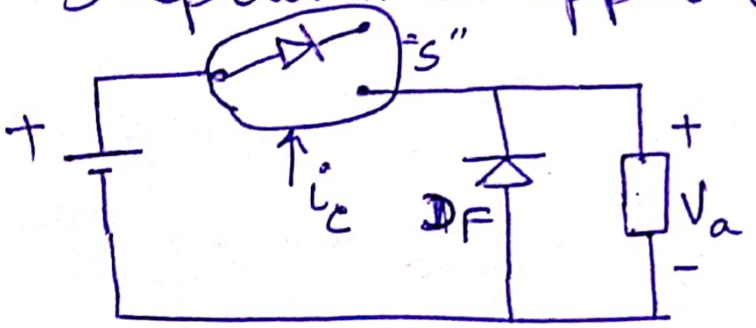


fig. Combined Arm & field control of dc motor drive.

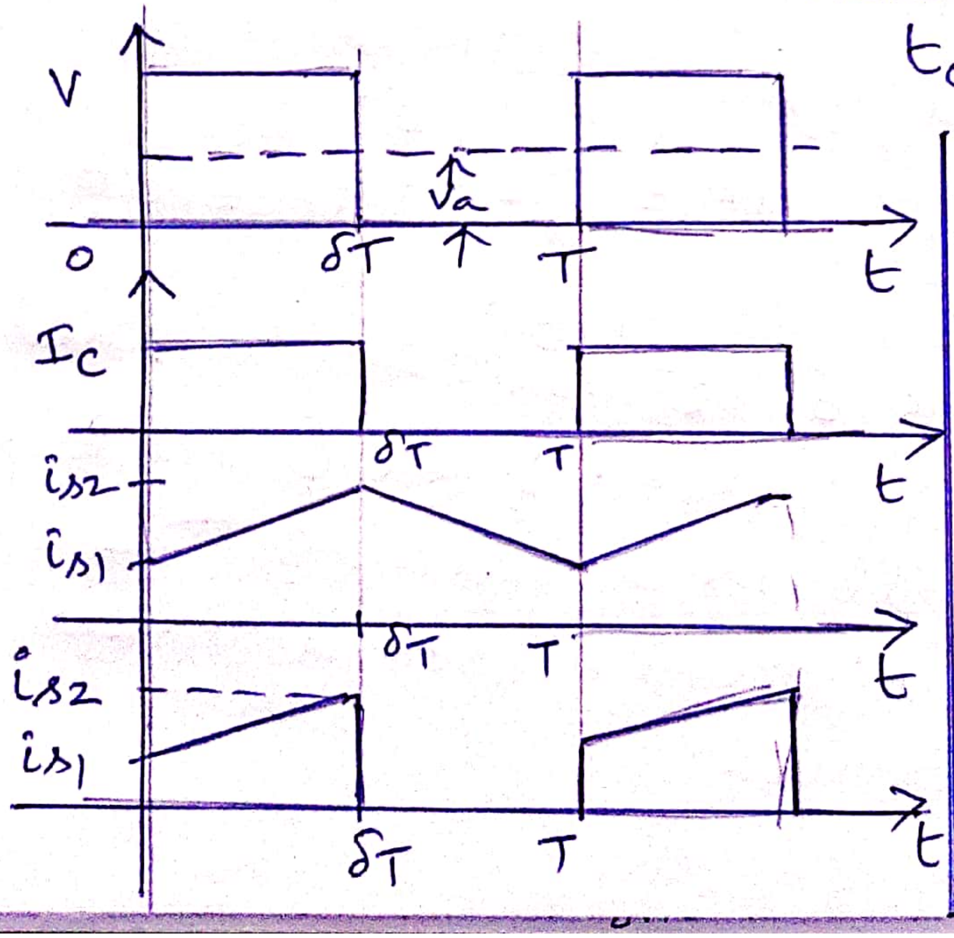
④ Chopper Control of DC Motors.

- Used because of a number of advantages like high efficiency, flexibility in control, light weight small size, quick response & regeneration down to very low speeds.

Stepdown Chopper (or) Class "A" Chopper.



"S" is self commutated semiconductor switch is operated periodically over a period T & remains closed for $t_{on} = \delta T$ with $0<\delta<1$



$\delta = \frac{t_{on}}{T}$ is called duty ratio & duty cycle of chopper.

$0 \le t \le \delta T$ is duty interval

$\delta T \le t \le T$ is known as free wheeling interval

- The class A chopper has one chopper circuit which is capable of provi^d^ing only a positive voltage & a positive current. ∴ it is called as Single quadrant (DC to DC buck converter (or) Stepdown choppers)

- Chopper provides positive speed & positive torque from the seperately excited motor control in the first quadrant. This can vary the output voltage from V to zero.

Average value of load voltage

$$V_a = \frac{1}{T}\int_0^T V_a\, dt = \frac{1}{T}\int_0^{\delta T} V\, dt = \delta t$$

By controlling δ between 0 & 1, the load voltage can be varied from 0 to V thus the chopper allows a variable DC voltage to be obtained from a fixed DC voltage source.

From the graph,

- The source current is not continuous but flows in pulses.
- The pulse current makes the peak input power demand high & may cause fluctuation in the source voltage.
- The source current waveform can be resolved into DC & AC harmonics. The fundamental AC harmonic frequency is the same as chopper frequency. A LC filter is used to wipe out the radio frequency interference produced by AC harmonics when interacting with other loads. (Radio freq interference due to conduction & electromagnetic radiation)
- At higher chopper frequencies, harmonics can be reduced to a tolerable level by filters (i.e it is better to operate the chopper with highest possible frequency)

- The terminal voltage (V_T) is not a perfect DC. In addition to the dc component, it has the harmonics of the chopping frequency & its multiples. The load current also has ac ripples.

Switch "S" can be controlled in various ways by varying the duty ratio (δ)

- Time Ratio Control (TRC) also called as Pulse width modulation
  - Constant frequency TRC (Here the chopper period "T" is kept fixed & t_{on} is varied to control the duty ratio (δ))
  - Varied freq TRC (Here δ is varied either by keeping t_{on} constant & varying T (or) by varying both T_{on} & T)
    - In variable freq control with constant on-time, low output voltage is obtained at low values of chopper frequency
- Current Limit Control (CLC) (or) Point-by point Control
  - δ is controlled indirectly by controlling the load current between certain specified min & max values.

note The low frequency operation affects the motor performance. More over the operation of chopper with variable frequencies makes the design of the input filter very difficult. So variable freq control is rarely used.

- In CLC approach when I_L reaches a specified value (max value), the switch disconnects the load from the source & reconnects when the current reaches a specified minimum value. For a DC motor load, this type of control is, in effect, a variable frequency variable on-time control.

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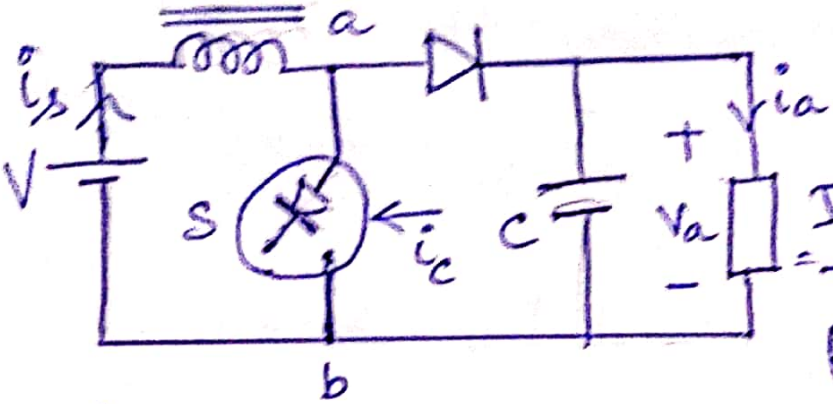
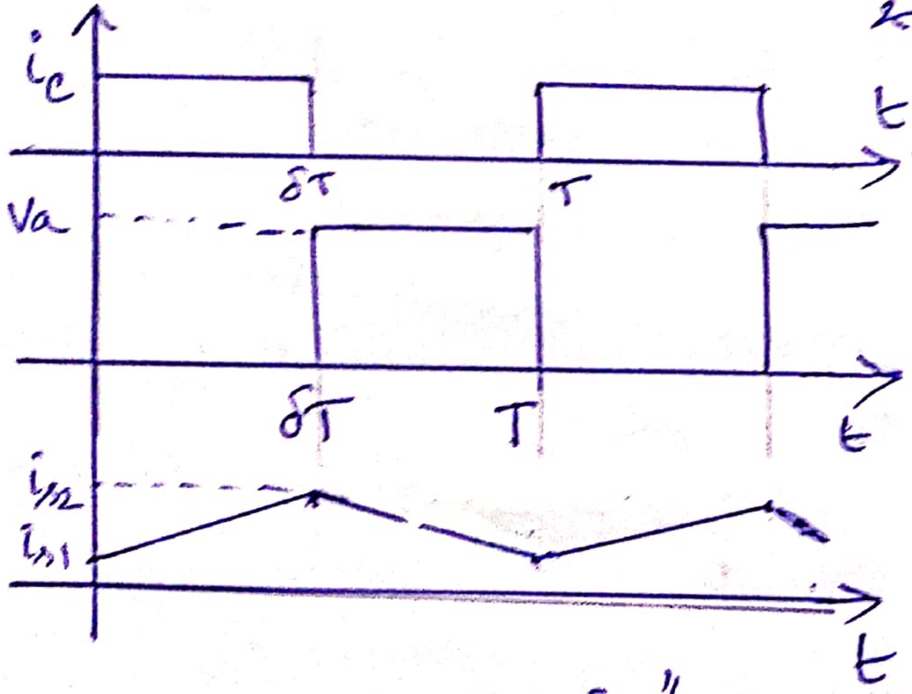
Class "B" Chopper
(or)
Step up Chopper





• With the control signal i_c switch "S" in forward bias.

During chopping period "T" it remains closed for $0 \le t \le \delta T$ & open for $\delta T \le t \le T$

• During ON period i_s increases from i_{s1} to i_{s2} increasing the magnitude of energy storage in the inductance

• When switch "s" is open, current flows through the parrallel combination of capacitor & load. Since the current is forced against the higher voltage, the rate of change of current is negative. It decreases from i_{s2} to i_{s1}. The capacitor serves 2 purposes

- At the instant of opening of "S", i_s and i_a are not same.
- In the absence of C, the turn off of "S" will force the 2 currents to have the same value. This causes high induced voltage in the inductance and load inductance
- The capacitor reduces the load voltage ripples.
- The diode D prevent any flow of current from the load into switch (S) or source (V).

The average voltage across "ab"

$$V_{ab} = \frac{1}{T}\int_0^T v_{ab}\, dt = V_a(1-\delta)$$

average voltage across inductor

$$V_L = \frac{1}{T}\int_0^T L\frac{di}{dt} = \frac{1}{T}\int_{i_{s1}}^{i_{s2}} L\, di = 0$$

Source voltage $V = V_L + V_{ab}$.

Substituting,

$$V = V_a(1-\delta) \quad \text{or} \quad V_a = \frac{V}{1-\delta}$$

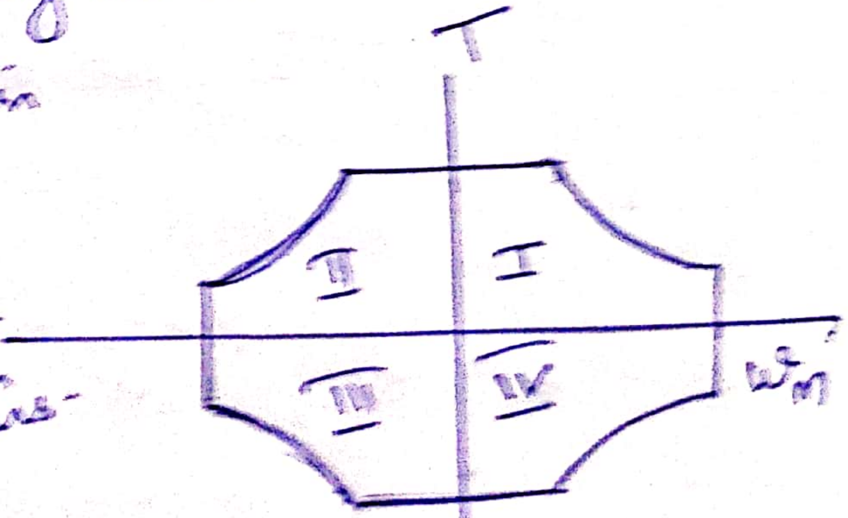
V_a changed from V to ∞ by controlling δ from 0 to 1.

main advantage of stepup chopper is the low ripple in source current.

used in low Power battery driven vehicle

But most of the applications require step down chopper.

Multiquadrant operation is preferred when DC motors are used in EV & HEVs including forward motoring, forward braking, backward motoring, backward braking as shown in figure.



II quadrant operation

forward motoring

forward braking

vehicle with reverse mech gears.

Q(I) & Q(IV)

4 quadrant without reversible gear.

Speed-Torque Profile of multi quadrant operation.

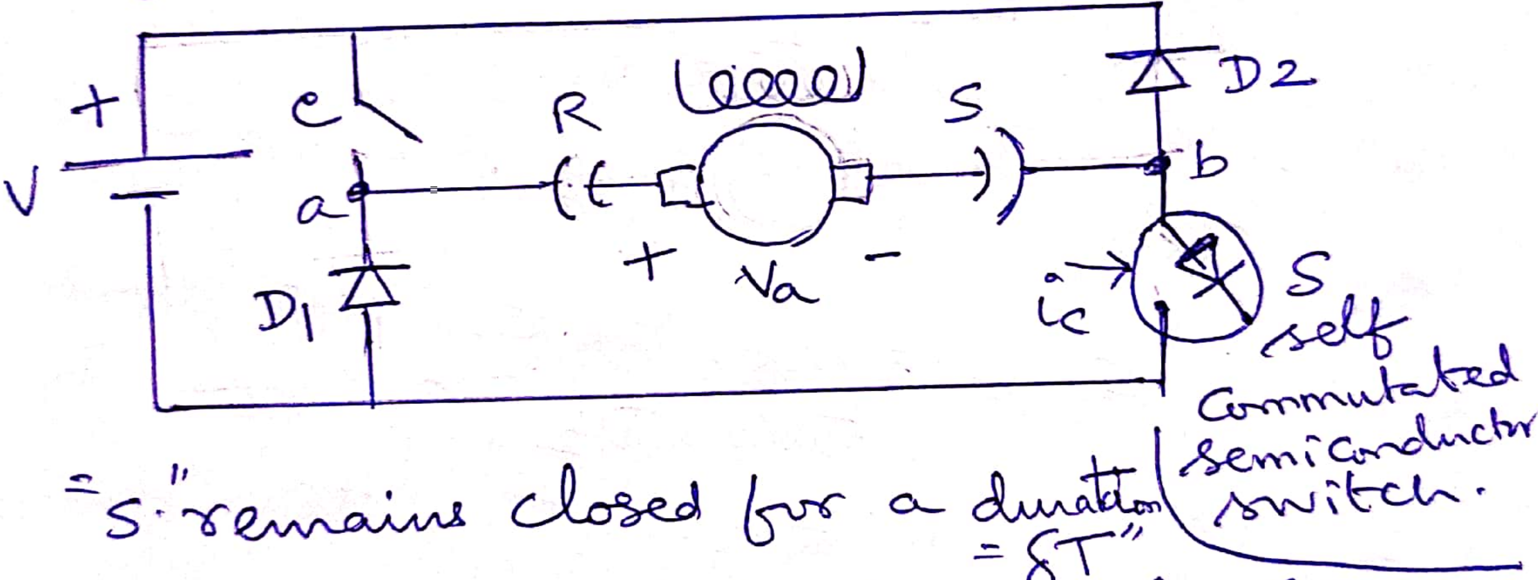
⑤ Two quadrant control of forward motoring & regenerative braking

Two schemes

Single chopper with a reverse switch

Class C 2 quadrant chopper.

Single chopper with a reverse switch.



"S" remains closed for a duration = δT"
& remains open for a duration (1-δ)T

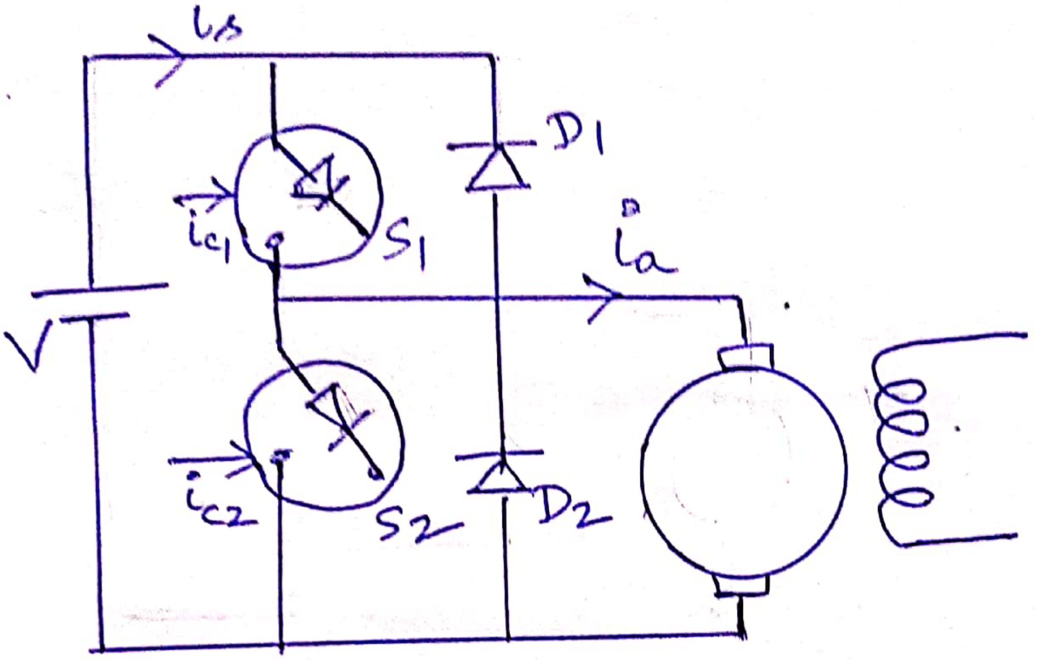
C is a manual switch.

- When C is closed & S is in operation the circuit is similar to that of Class A Chopper.
- Regenerative braking in forward direction is obtained when "C" is open & the armature connection is reversed with

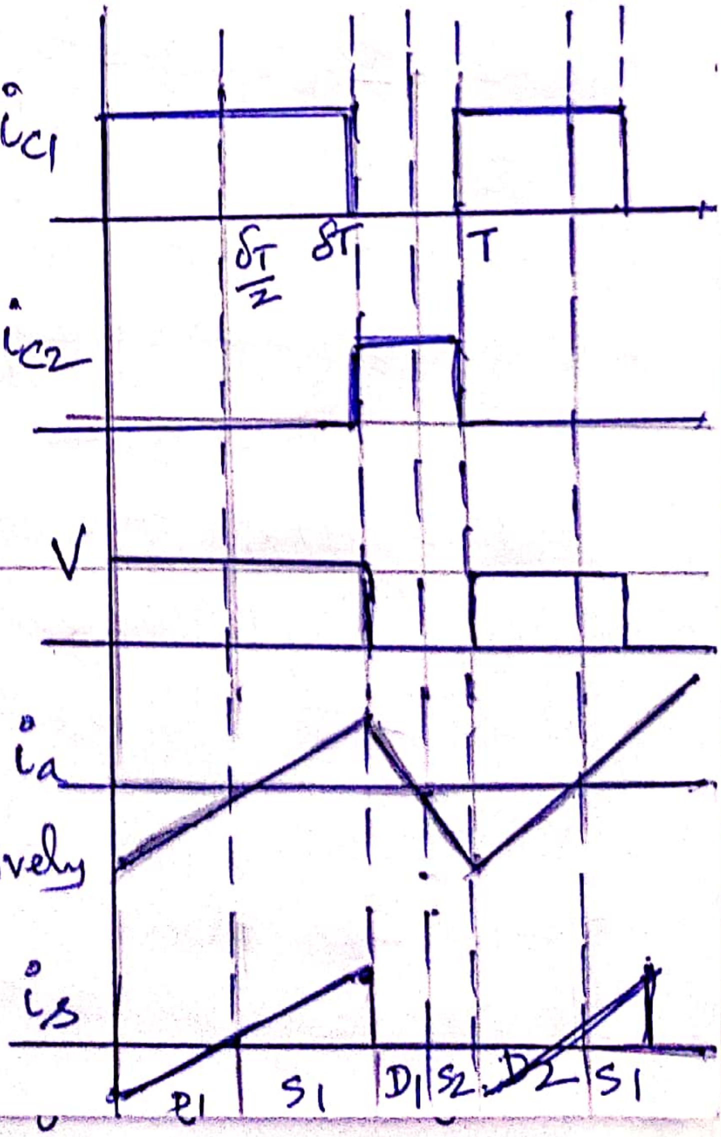
the help of reversing switch "RS" making "b" positive and "a" negative.

- During ON period of switch "S", the motor current flows through armature switch "S" & D_1 and increases the energy storage in the armature circuit inductance.
- During regenerative braking switch "S" is deactivated and switch "C" is opened.
- When "S" is open the current flows through armature, D_2, Source voltage D_1 and back to armature thus feeding energy to the source.

Class "C" 2 quadrant chopper.



- For smooth transition from motoring to braking & vice versa class C 2 quadrant choppers are used
- Both choppers S_1, D_1 and S_2, D_2 are controlled simultaneously both for motoring & regenerative braking



S_1, S_2 are closed alternatively

S_1 ON for δT

S_2 ON from δT to T

- To avoid direct short circuit across the source care to be taken to ensure that S_1 & S_2 donot conduct at the same time this is done using delayed on & off switches (but are of very small delayed interval)

2 quadrant circuit Highlights:

- In this discontinuous conduction (occurs when Ia falls to zero & remains zero for a finite interval of time) does not occur irrespective of its frequency of operation
- The current may becomes zero either during the free wheeling interval or in the energy transfer interval (free wheeling occares when S_1 is off & current flows through D_1 during $\delta T \leq t \leq T$)
- If Ia fails to zero in free wheeling interval back emf will immediately

drive the current through "S_2" in reverse direction, thus preventing I_a to zero for a finite interval of time.

$|||^{ly}$ energy transfer will be present when S_2 is off & D_2 is conducting during $0 \leq t \leq \delta T$

If current falls to zero during this interval "S_1" will conduct immediately because of "i_c" due to $V > E$; and I_a flows preventing discontinuous conduction.

- As no discontinuous conduction I_a flows all the time during $0 \leq t \leq \delta T$ connected through S_1 or D_2 the rate of change of i_a will be positive as $V > E$
- During $\delta T \leq t \leq T$ the motor armature shorted through D_1 or S_2 consequently $V_m = 0$ & rate of change of i_a is negative.

- During $0 \leq t \leq \delta T$ positive I_a carried by S1 and negative I_a carried by D_2

- During $\delta T \leq t \leq T$ positive I_a carried by D1 and negative I_a carried by S_2

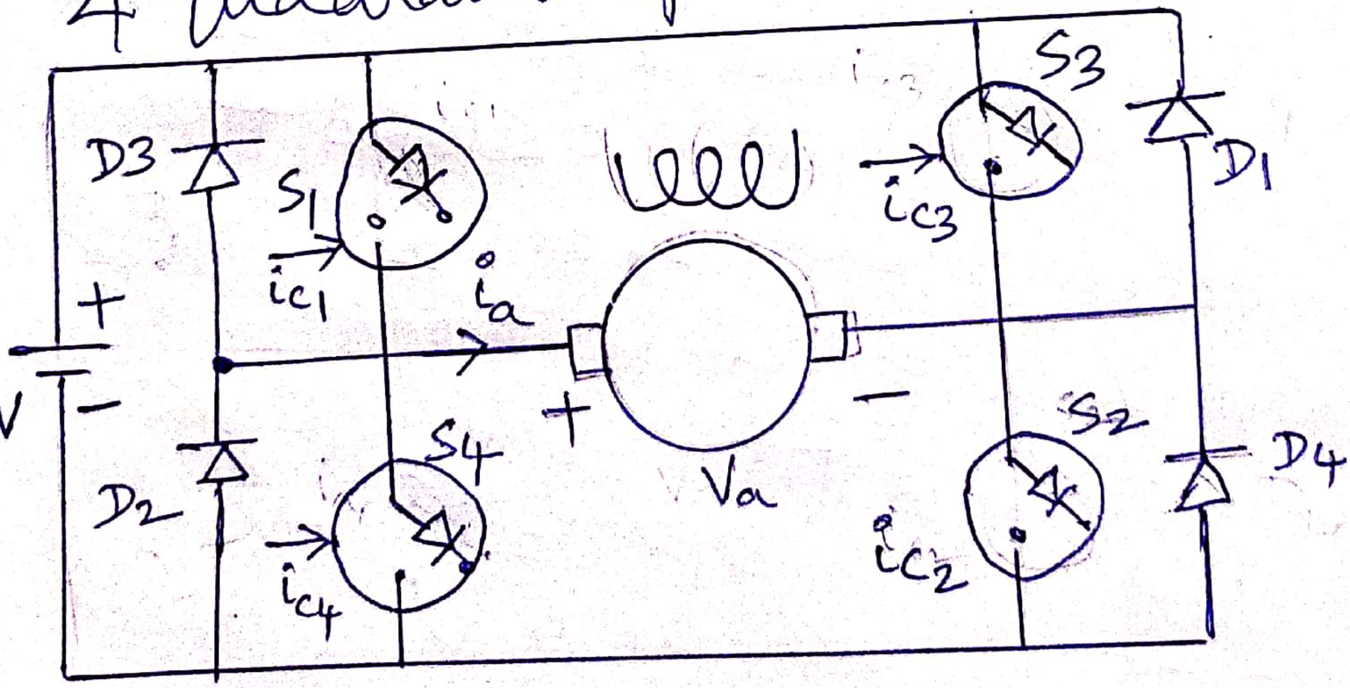
$$I_a = \frac{\delta V - E}{R_a}$$

motoring during $\delta > \frac{E}{V}$

Regenration during $\delta < \frac{E}{V}$

& no-load operation when $\delta = \frac{E}{V}$.

4 quadrant operation (or) Class E



- This can be obtained by Combing 2 Class C Choppers which is refered as Class E Choppers
- If S_2 kept closed Continiously & S_1 & S_4 are Controlled, 2 quadrant chopper is obtained, which provides positive Terminal Voltage (V_T) & positive Speed & I_a in any direction (positive or negative torque) giving motor control in quadrants I & IV
- If S_3 is kept Closed Continously S_1 & S_4 are Controlled, 2 quadrant chopper is obtained supplying a Variables negative V_T (negative Speed) & I_a in any direction (positive or negative torque) giving motor Control in quadrants II & IV
- Due to the asymmetry in the circuit operation low usage of few switches. But S_3 & S_2 should remain ON for a longer period which creats Commutation

Problem when the switches uses with thyristor.

- Minimum output Voltage depends directly on the minimum time for which the switch can be closed (restriction on the minimum time for which the switch can be closed. As minimum output voltage and therefore the minimum available motor speed is restricted.
- Ensure S_1 & S_4 or S_2 & S_3 not operates at the same time requires delay in switching.

— × —

⑥ Recent EV motors:

- DC Commutator Motor (DC Motor) Control Principle is simple because of the orthogonal disposition of field & armature mmfs.
- By replacing the field winding of dc motor with Permanent Magnets (PM)s. PM motors permit a considerable reduction in stator diameter due to the efficient use of radial space.
- Because of the low permeability of PMs, armature reaction is usually reduced & commutation is improved.
- DC Motors have the basic problem with Commutators, brushes which makes them less reliable.
- But recent technological development resulted in developing Commutatorless motor to ensure high efficiency;

high power density ; low operating cost more reliable & maintenance free over dc commutator motors.

- Induction Motors are widely used for propulsion because of their low cost, high reliability & free maintenance. But conventional control of Ind motors such as Variable-Voltage variable-frequency (VVVF) cannot provide the desired performance one major reason is due to the nonlinearity of their dynamic model.
- with the advanced technology like μP, remote controlling the principle of Field oriented Control (FOC) also called as Vector Control (or) decoupling Control of Ind. motor has been accepted to overcome their control complexity due to the nonlinearity.

- Ind motors employed with FOC suffers from low efficiency & limited Constant-power operating region.
- On-line efficiency-optimizing control scheme when adopted results in 10% less energy consumption & 4% increase in regenerative energy.
- When electrically pole changing scheme adopted can significantly extend the constant-power operating region to over 4 times the base speed.
- By replacing the field winding of the conventional synchronous motors with PMs, PM syn motor can eliminate conventional brushes, sliprings & field Cu loss. These PM syn motor are also called as PM brushless AC motors (or) sinusoidal-fed PM brushless motors because of their sinusoidal ac current

& brushless Configuration.

- These motors Can run from a Sinusoidal (or) PWM supply without electronic Communication.
- When PM are mounted on the surface of the rotor they behave as non-salient syn motor as the ~~per~~permeability of the PMs is similar to that of air.
- When these PMs are burried inside the magnetic circuit of the rotor the saliency Causes an addisional reluctance torque which gives a wider speed range at Constant-power operation.
- But the field winding or PMs are abandoned while purposely making use of the rotor saliency, Synchronus Reluctance Motors are obtained. These motors are simple & cheap but relatively low output power.

- Similar to Ind Motors, PM syn motors usually employ FOC for high performance application because of their inherent high power density & high efficiency to compete with Ind. Motors for EV application. Self tuning Control has been developed for PM syn motor.
- By virtually inverting the Stator & rotor of PM DC motor, PM brushless DC motors are obtained. These motors are fed by rectangular ac current (not dc as the name implies) & hence called as Rectangular-Fed PM brushless motors.
- Advantages of these motors are that there is no brushes, so problems associated with brushes are eliminated. Moreover the rectangular interaction between current & flux have an ability to produce larger torque.

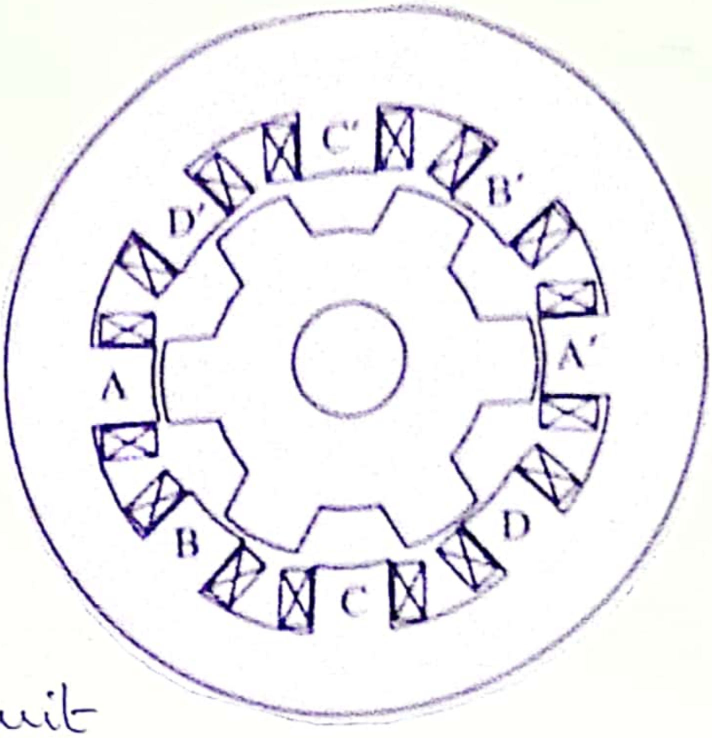
Also the brushless Configuration allows more cross sectional area for armature. As the Conduction of heat through frame is improved, an increase in electrical loading causes high power density.

- Presently phase-decoupling PM brushless dc motors have been developed for EVs which provides outstanding powerdensity, no Cogging torque, excellent dynamic performance with extended range of speed at Constant power operation.

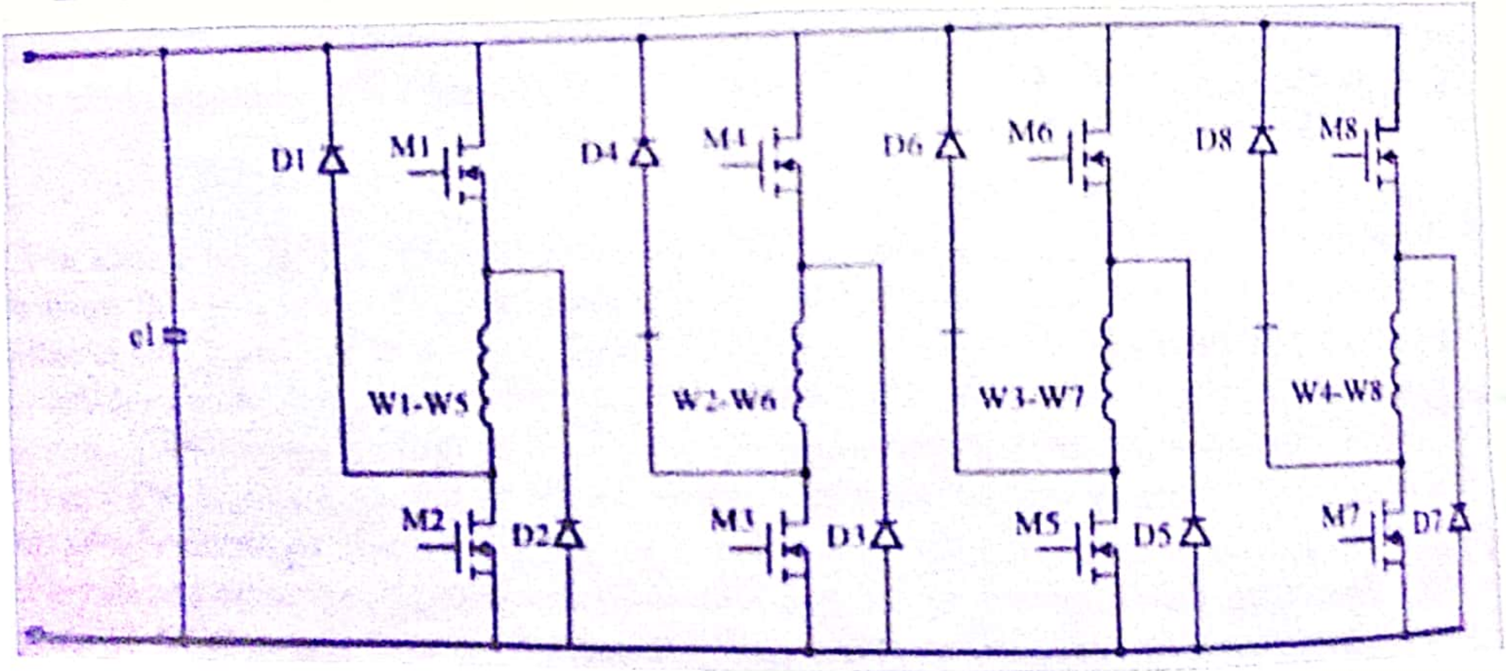
Switched Reluctance Motor (SRM)

- They are direct derivatives of single-stack variable-reluctance stepping motors
- SRM simple Construction, low manufacturing cost, & outstanding Torque-speed characteristics for EV usually exhibit acoustic noise Problem.

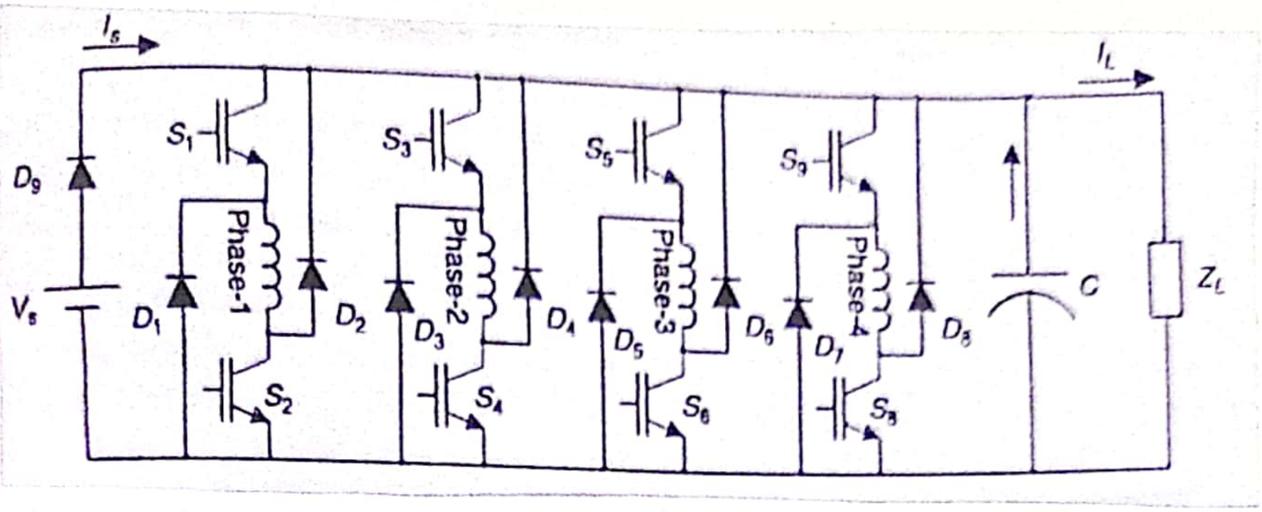
Fig. The cross section of a 6/8-Pole SRM



SRM Control Circuit



Driving circuit for Switched Reluctance Generator (SRG)



⑦ Induction Motor drive

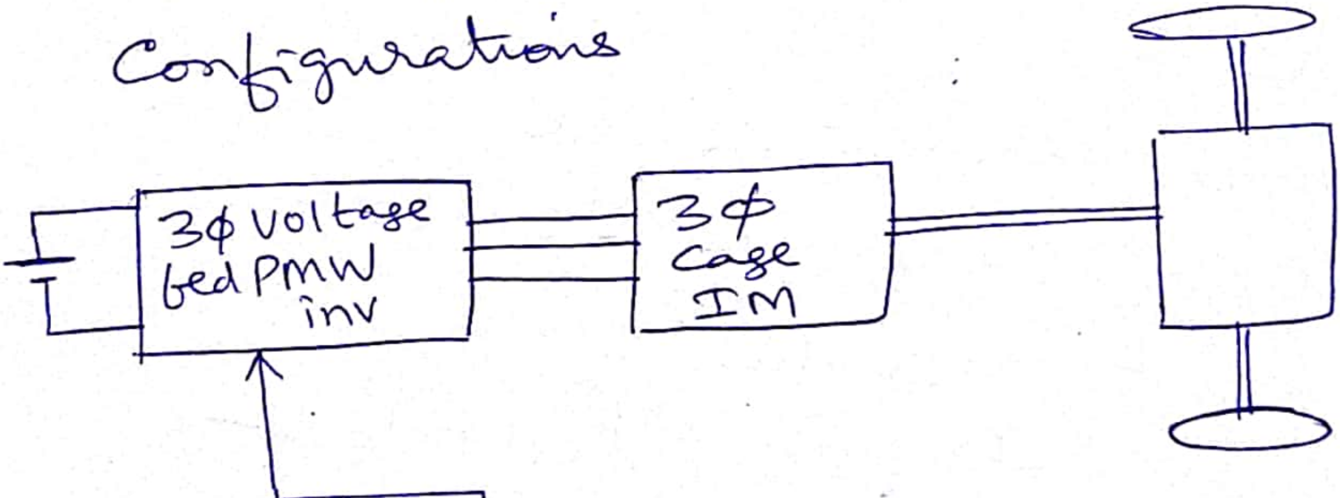
- Commutatorless motor drive is more advantages over the conventional dc Commutator motor drive for elec propulsion.
- Ind motor drive is found to be the most mature technique among Commutatorless motor drives.

Ind motors

Wound rotor
(Because of high cost lack of sturdiness it is inferior to cage)

Squirrel cage
(widely used)

Configurations



System Configuration of Ind motor drive for EV propulsion can be divided into

Single motor system
(Refer above figure)

multiple motor system
(multiple motors multiple inverters centralized or distribut controllers & optional reduction gears)

With the development of soft switching inverters for Ind motor drives resonant dc links are used. Further development

quasi - resonant dc link
series - resonant dc link
Parallel - resonant dc link
synchronized - resonant dc link
resonant transition
aux. resonant commutated pole &
Auxillary Resonant Snubber Inverter (ARS)

Among this ARS is widely used to achieve soft switching Condition.

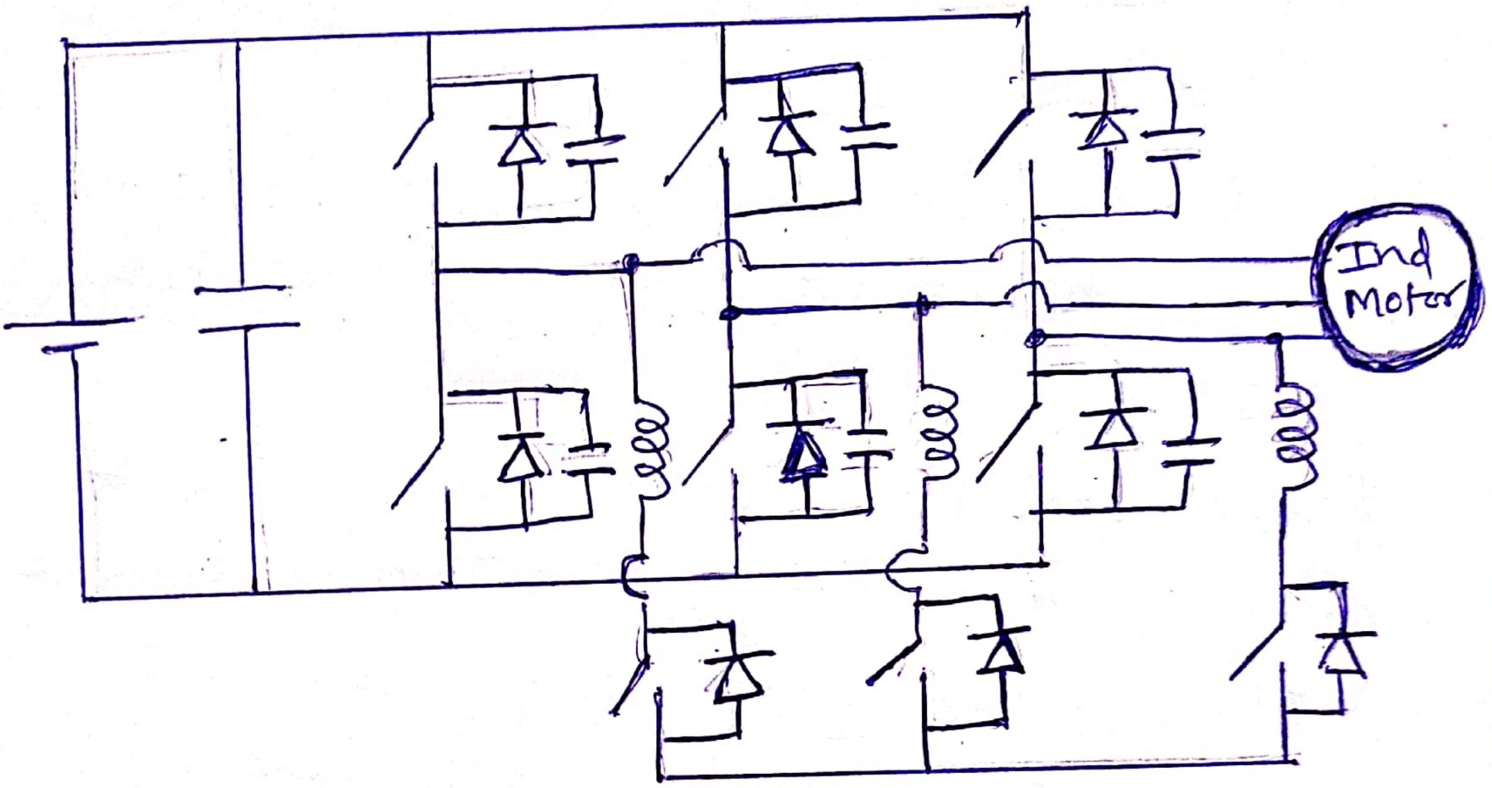


fig 3ϕ ARS inverter topology
(⅄ Configuration)

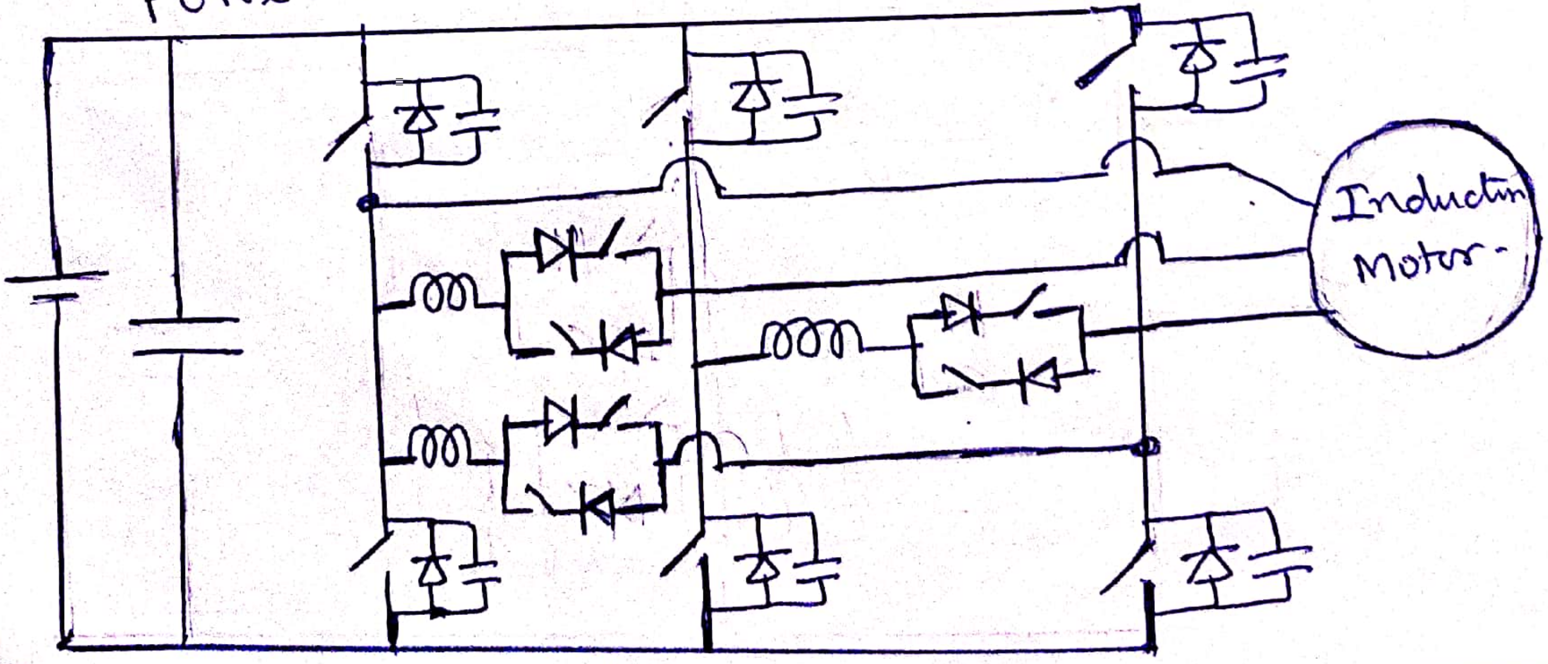
- To achieve soft switching auxillary switches & resonant inductors are used along with resonant snubber capacitors 2 in 3ϕ topologies of the ARS inverter is used as shown above.

The inverter topology offer

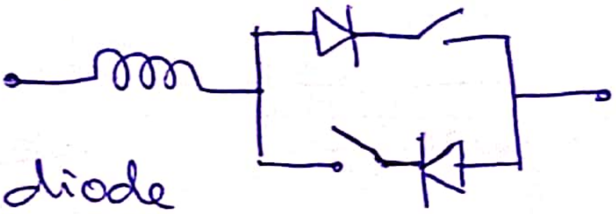
① all main power devices can operate at Zero voltage Switching (ZVS) Condition. &

② all auxillary power switches also operate at Zero Current Switching (ZCS) Condition.

- Moreover parasitic inductance & stray capacitor of this topology are utilized as a part of the resonant components, while there are less over voltage or over current penalty in the main Power switches.



Delta (Δ) ARS inverter is more attaractive as it have high power capability, no-floating voltage or over-voltage penalty on the auxillary power switches. No need to use addisional voltage or current sensors. No need to use antiparallel fast reverse recovery diode across the resonant switches.



Speed Control :

- Speed Control of Ind Motors is more Complex than that of dC motors because of the nonlinearity of the dynamic model between direct & quadrature axes.

Types

Variable Voltage
Variable frequency
(VVVF)

Field oriented Control
(FOC)
or
Vector Control
(or)
Decoupling Control
(or)
Pole Changing Control.

Basic equation of Speed Control

$$N = N_s(1-s) = \frac{120f}{P}(1-s)$$

Motor speed can be varied by controlling frequency (f), Pair of Poles (P) and/or slip (s)

[More than one of these control variables are adopted]

Moreover adaptive control, Variable Structure control & optimal control can also be employed to achieve faster response, high efficiency & wider operating ranges.

VVVF Control

- This is based on constant voltage/frequency control for frequencies below the motor rated frequency whereas variable frequency control with constant rated voltage for frequencies beyond rated frequency.
- For very low frequencies, voltage boosting is applied to compensate the difference

between the applied voltage & induced emf due to stator resistance drop.

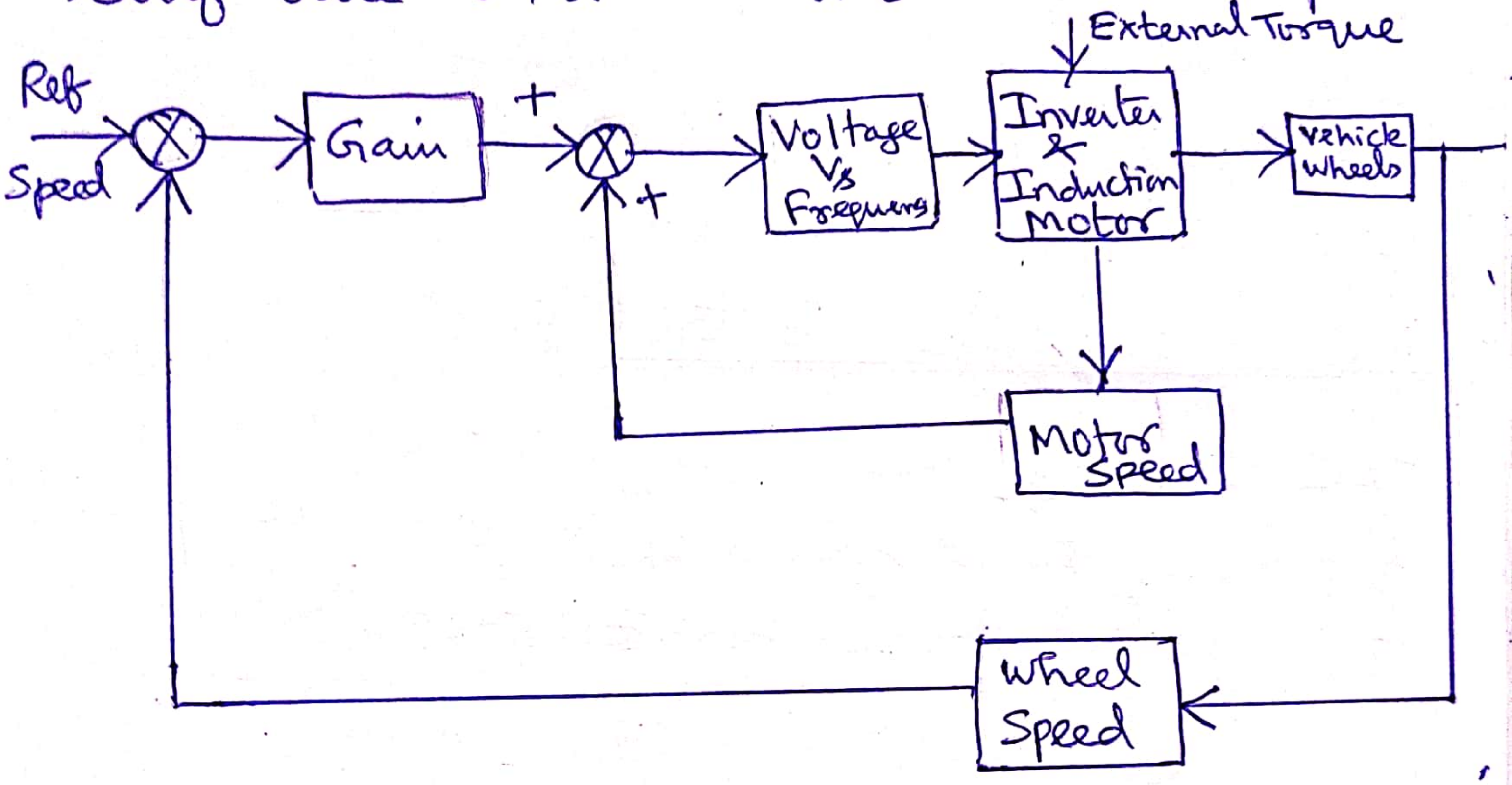
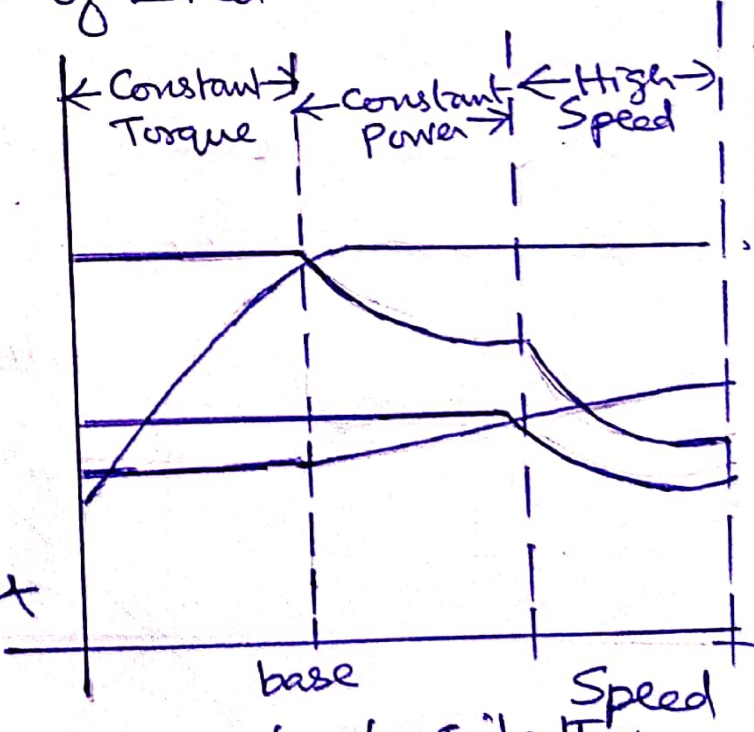


Fig. VVVF Control of Ind motor drive



Constant Torque region:

The motor can deliver its rated torque for frequency below rated frequency.

Constant Power region:

The slip is increased to the max value in preset value so that the stator current remains constant & motor can maintain its rated power capability

High Speed region: slip remains constant while the stator current decreases. The torque declines with the square of the speed.

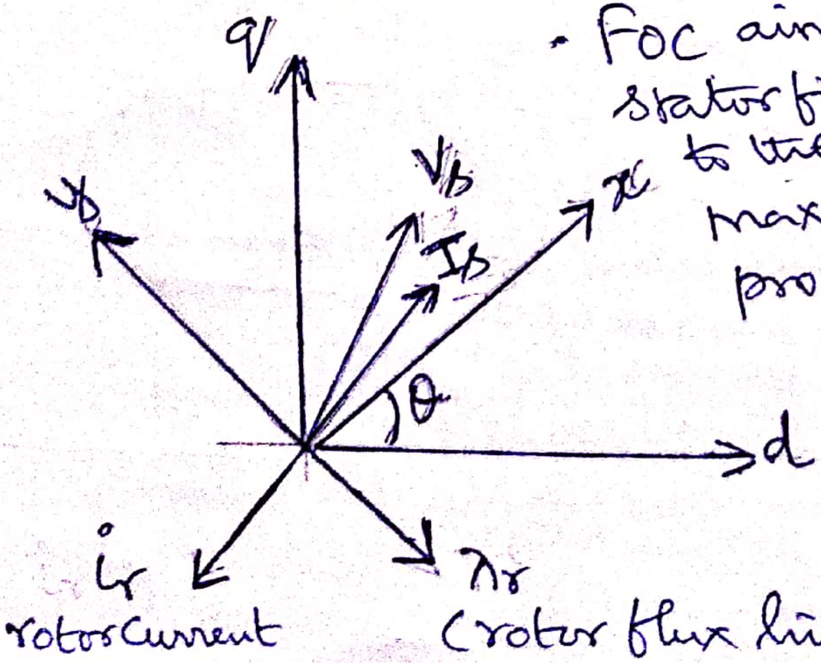
Disadvantage of VVVF:

As the airgap flux drifts & sluggish response VVVF control strategy is less of use for EV Ind. motor drive.

Field oriented Control (FOC)

- FOC is preferred than VVVF Control to improve the dynamic perfomance of Ind motor drives for EV propulsion.
- With this FOC, the mathematical model of Ind motor is transformed from stational reference (d-q) frame to general synchronously rotating frame (x-y)

- FOC aims to maintain stator field perpendicular to the rotor field so that max torque is always produced by the motor



When the x axis is purposely selected to be Coincident with rotor flux linkage vector, the reference frame (α-β) becomes synchronously with the rotor flux.

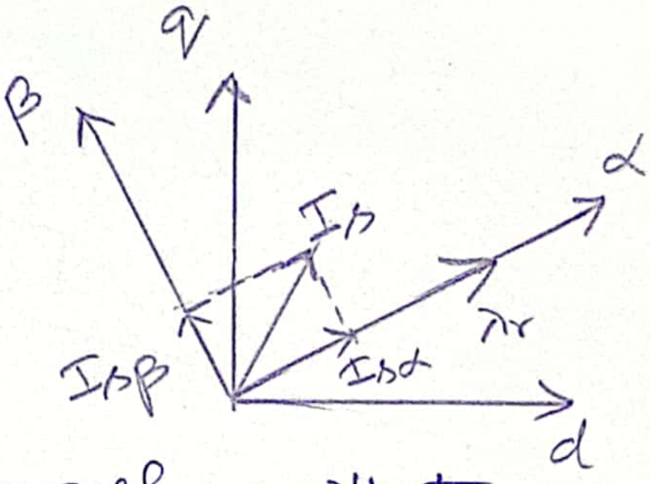


Fig represents α-β frame rotating synchronously with rotor flux.

$I_{s\alpha}, I_{s\beta}$ → α axis & β axis Component of stator current respectively.

Motor Torque $T = \frac{3}{2} P \frac{M}{L_r} \lambda_r i_{s\beta}$

where M → mutual Inductance / phase

L_r → rotor Inductance / phase

as $\lambda_r = M i_{s\alpha}$; $T = \frac{3}{2} P \frac{M^2}{L_r} i_{s\alpha} i_{s\beta}$

The torque eqn is similar to that of seperately excited dc motor

($i_{s\alpha} \simeq I_f$; $i_{s\beta} \simeq I_a$)

The motor torque is effectively Controlled by adjusting the torque Component remains constant.

FOC

Direct FOC (requires direct measurement of rotor flux. This is difficult to obtain measurements at low speeds. So not widely used)

Indirect FOC (Rotor flux is calculated instead of direct measurement This is widely used)

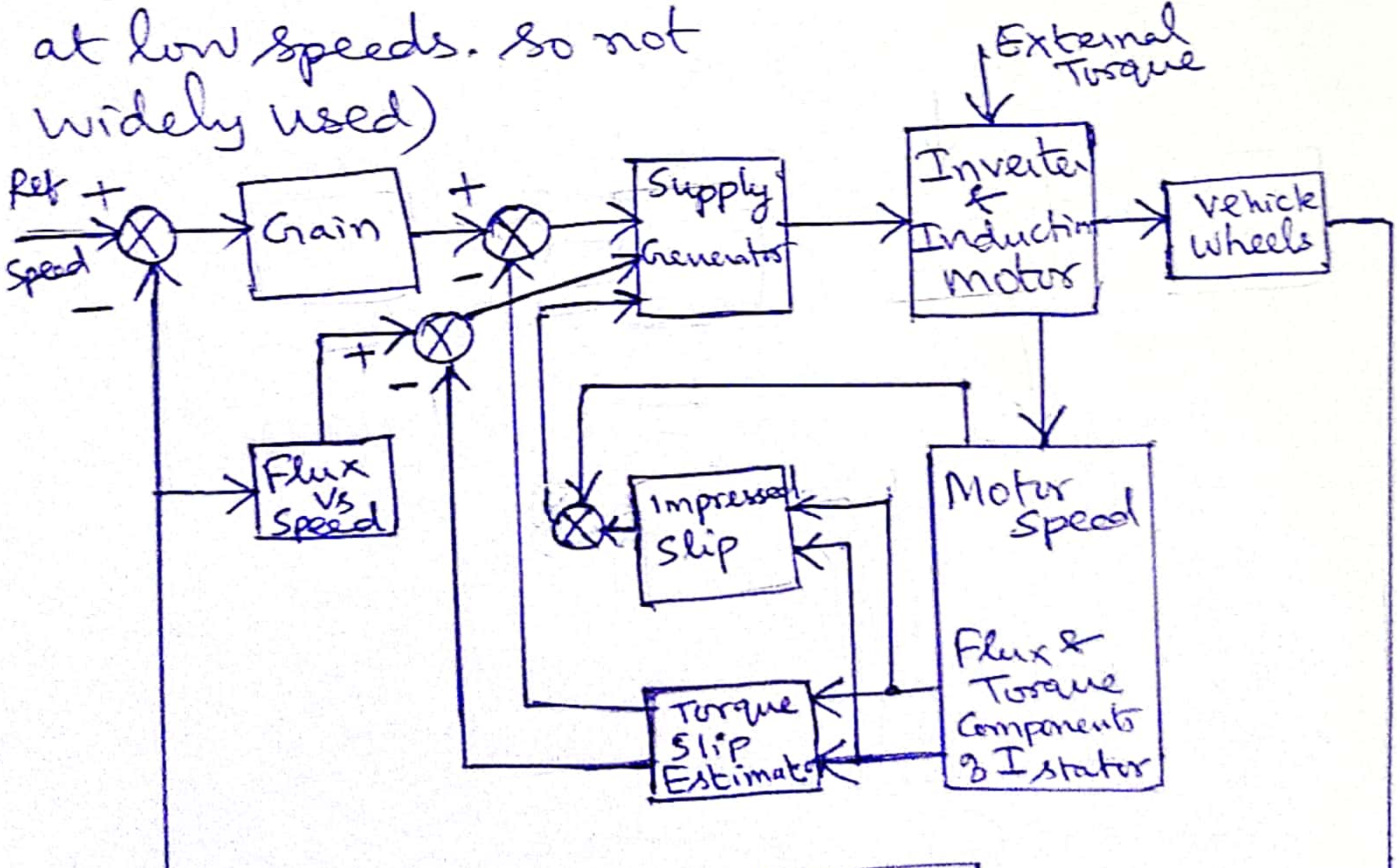
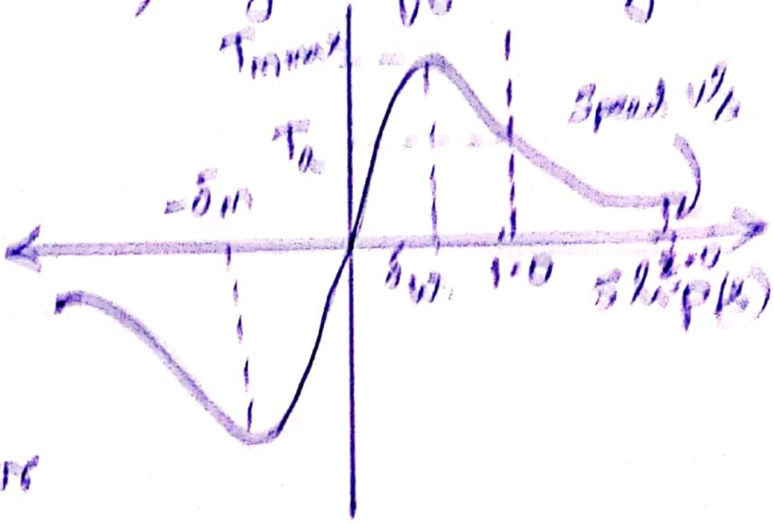


Fig : FOC of Ind. Motor drives.

⑧ Induction Motor Drives

- Commutator less motor drives offer a number of advantages over conventional DC commutator motor drives for electrical propulsion of EV & HEVs.
- AC Ind motor drive have light weight, small volume, low cost, high efficiency.



mechanical angular velocity $W_{ms} = \frac{2}{P} w$

$= \frac{4\pi f}{P}$ rad/sec

Angular velocity of rotor

$W_m = \frac{2}{P} w(1-s)$

when angular velocity of rotor = mechanical angular velocity of rotating stator mmf

no induced current in rotor & no torque is produced

Torque developed $(T) = \frac{P_{mech}}{W_m}$ $W_m \rightarrow$ rotor speed.

Slip $(S) = \frac{W_{ms} - W_m}{W_{ms}} = \frac{\text{slip speed } (W_{sl})}{W_{ms}}$

→ mech angular velocity of rotating stator mmf is also called as synchronous speed.

For

$\omega_m < \omega_{ms}$; Relative Speed is positive
Rotor induced Voltage have same phase sequence as stator voltage &
Torque is positive.

$\omega_m = \omega_{ms}$; Relative speed between rotor & Stator field is Zero.
No Voltage is induced &
No Torque is produced.

$\omega_m > \omega_{ms}$; The relative speed between stator field & rotor speed reverses.
Rotor induced Voltage have Phase sequence opposite to that of Stator.
Torque is negative suggests generator action.

Permanent Magnet Hybrid Motors.

PM & Reluctance Hybrid Motors (or) Double Salient PM motors	PM & Hysterisis Hybrid motors	PM & field winding Hybrid Motors
(PMs are burried inside the magnetic circuit of the rotor both PM torque & syn-reluctance torque will be available Incorporates PMs into SR structure to have PM & Reluctance Hyb motor.	Incorporates PM & hysterisis torques by the placement of PMs in the inner surface of the hysterisis ring. **Adv** • High starting torque & smooth operation. —x—	Comprises both PMs in the rotor & dc field winding in the inner stator by controlling the direction & magnitude of the dc field current, the airgap flux can be adjusted flexibily & Torque-speed charateristics can be easily shaped to meet special requirements

There are six types of grading system (Max: 5) are adopted to evaluate various motors used in EV.

Type	Cost	Power Density	Effici	Controllability	Reliability	Maturity	Total
Dc Motor	4	2·5	2·5	5	3	5	22
Ind motor	5	3·5	3·5	4	5	5	$\boxed{26}$
PM Brushless motor	3	5	5	4	4	4	25
SRM	4	3·5	3·5	3	5	4	23
PM Hybrid motors	3	4	5	4	4	3	23

— x —

Permanent Magnet Brushless DC Motor (PMBLDC) Drives.

- Using high-energy PM as the field these motors are designed with high power density, high speed & high operating efficiency.

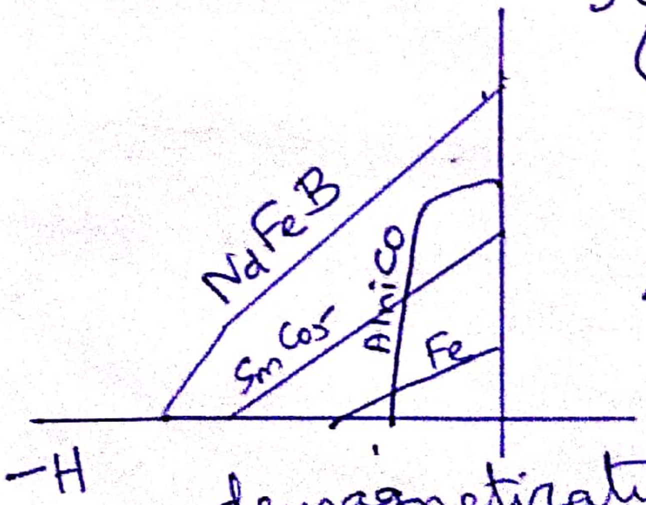
Advantages

- No Power Consumption due to PM
- Absence of mech commutator & brushes so low mech friction losses & ∴ high efficiency.
- High energy density Magnets

Alnicos
(Al, Ni, Co, Fe)

Ceramics
(Ferrites)
Barium Ferrite
($BaO \times 6Fe_2O_3$)
Strontium Ferrite
($SrO \times 6 Fe_2O_3$)

Rare Earth magnets
Samarium Cobalt
($SmCo_5$)
&
Neodymium iron-boron
(Nd Fe B)



demagnetigation Curve

Alnico	Ferrites	Rare - Earth PMs.
Used during 1940-70s High magnetic Remanet flux density & low temperature coefficient (or) Remanence 0.02%/°C Maximum Service Temperature is 520°C Allows high airgap flux density & high operating temperature. • But coercive force is very low • Demagnetizing Curve is extremly nonlinear. • No easy for magnetizing & demagnetizing • Used in EV ranges from few to 150KW	$BaO \times 6Fe_2O_3$ Barium ferrite & $SrO \times 6Fe_2O_3$ Strontium Ferrite invented in 1950s Has higher Coercive force than Alnico. But has a lower remanent magnetic flux density & temp Coeffs are relatively high ($B_r = 0.2\%/^\circ C$) The Coefficient of Coercive field strength (H_c) or Coercivity is 0.27%/°C maximum Service temperature 400°C low cost; very high elec resistance & no eddy current loss in PM	Samarium Cobalt invented in 1960s High Remance flux density High Coercive force High energy production Linear demagnetization curve & low temp Coefficient Temp Coeff of $B_r = 0.03$ to $0.045\%/^\circ C$ Temp Coeff of $H_c = 0.14$ to $0.4\%/^\circ C$ Max Service Temp 250 to 300°C Costly. II generation Nd Fe B better magnetic property than SmCos Temp Coeff of

		$B_r = 0.095$ to 0.15 %/°C Temp Coeff of $H_c = 0.4$ to 0.7 %/°C Max Service Temp = 150°C Curie Temp is 310°C

Note Rare-earth magnets achieves very high flux densities in BLDC Motors

Advantages of BLDC Motors:

Ease of Control: BLDC Can be Controlled as easy as a DC motor as the Control variables are easily accesible.

Ease of Cooling: As no current flows in the rotor, the rotor of BLDC motor doesnot heat up. Heat produced in the Stator Can easily be controlled.

Low maintenance, Longevity & Reliability: Because of the absence of brushes & mech Commutators no much maintenace is required. Longevity is only function of winding insulation; bearings &

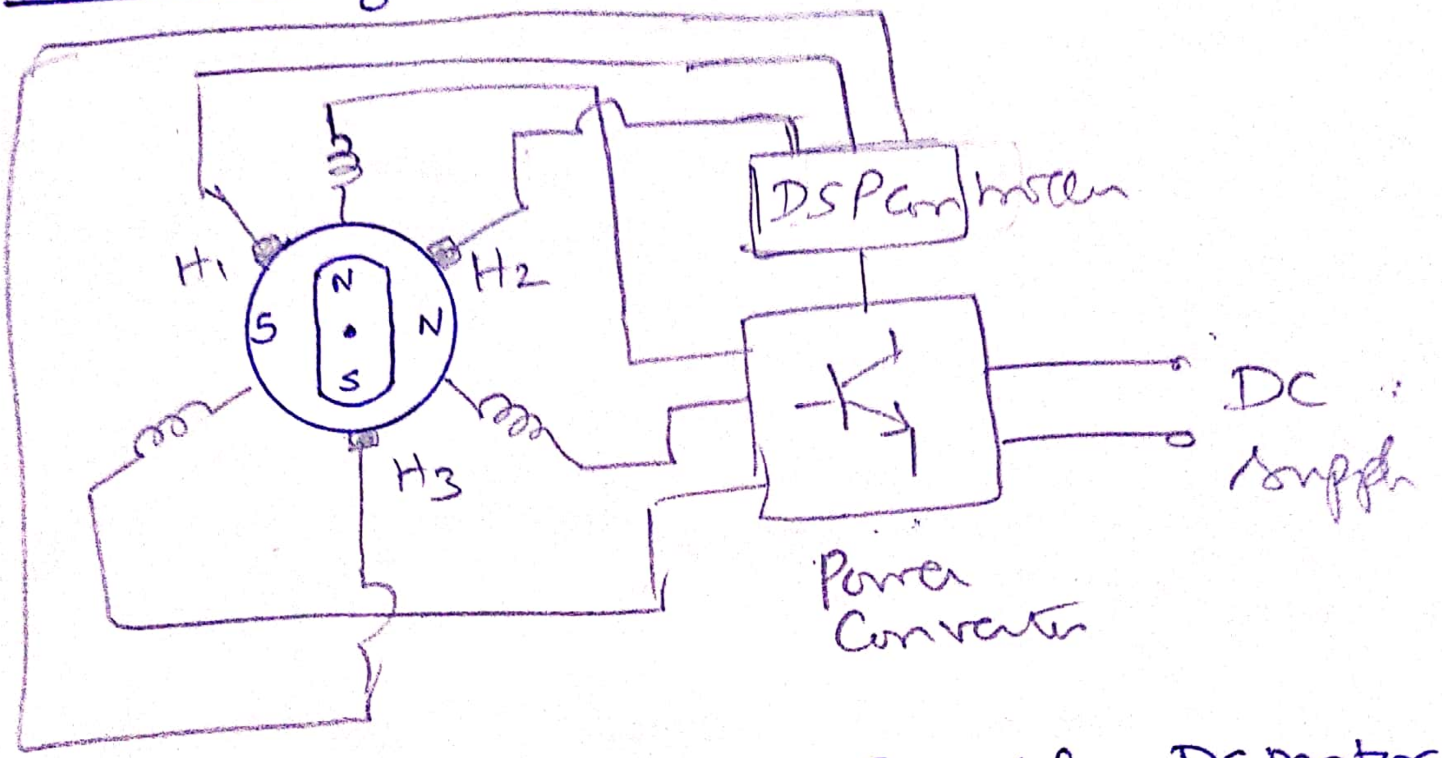
magnet life-length.

Low noise emissions: No noise is associated with the Commutation because of its electronic components & not mech components. The driving Converter switching frequency is high enough so that the harmonics are not audible

BLDC disadvantages:

- Cost high due to the usage of rare earth magnets.
- PMBLDC is incabable of achieving maximum speed which is greater than twice the base speed.
- Magnet demagnetizing can be done by large opposing mmf & high temperature.
- Cooling of motors requires special skill.
- High speed capacity due to surface mounted PM.
- Inverter failure in BLDC motor due to short circuit failures.

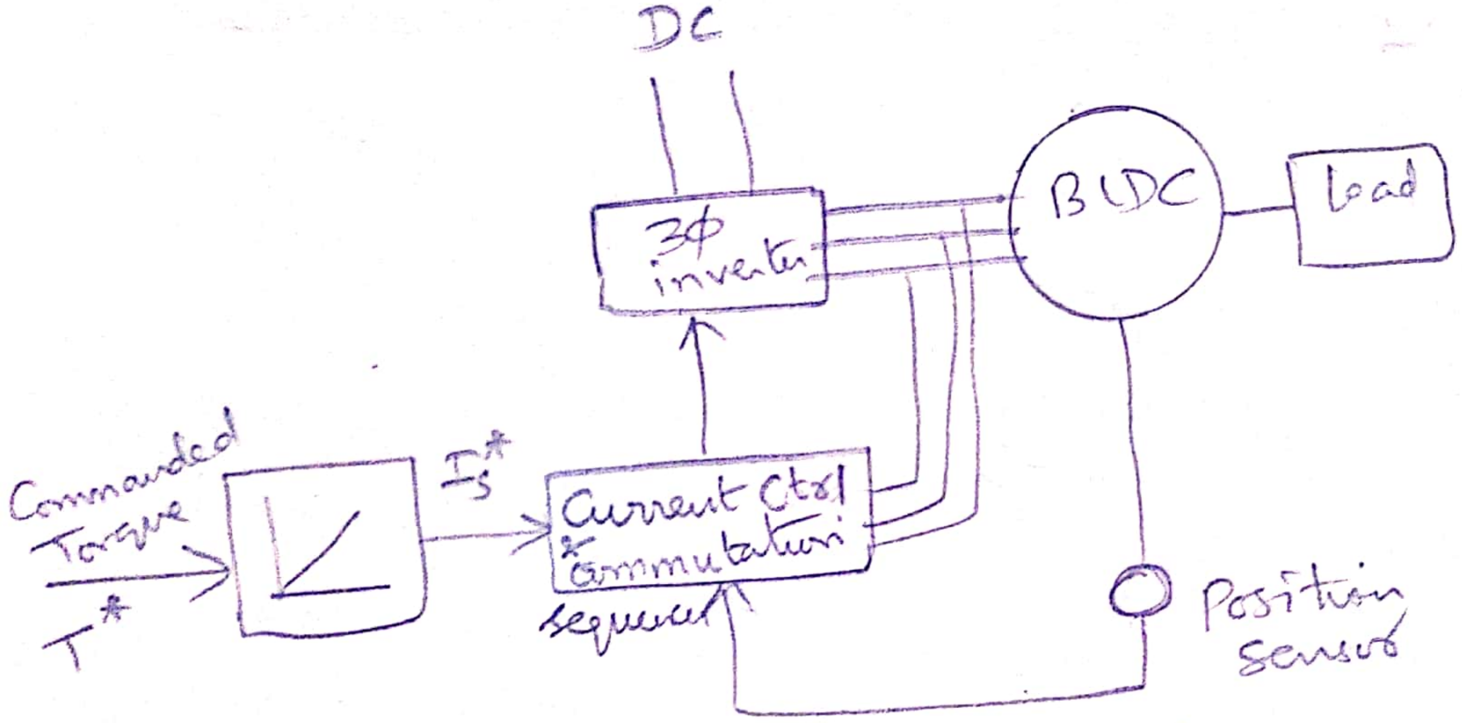
Control of BLDC motor drives.



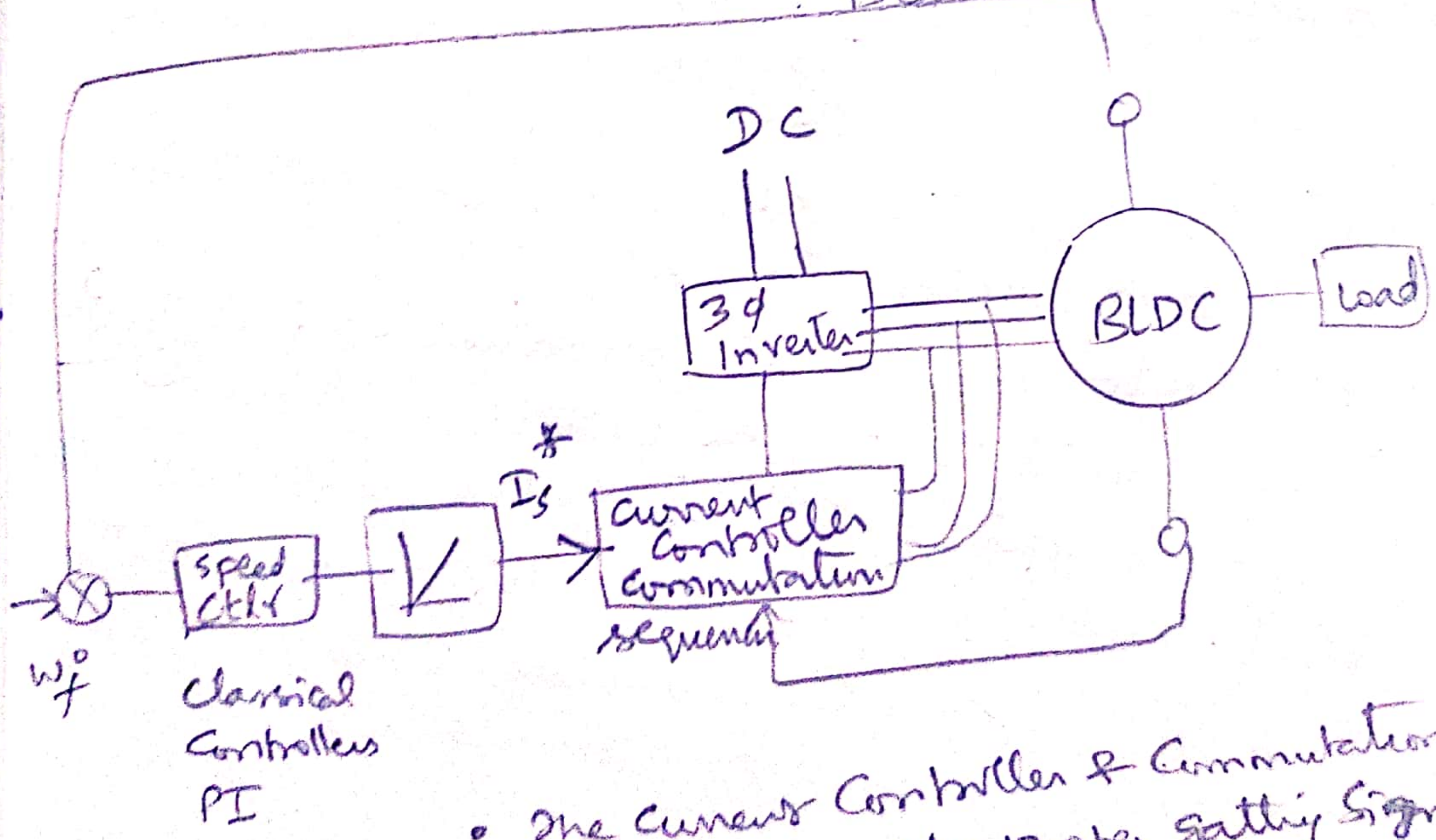
A BLDC motor drive. } Consists of Brushless DC motor DSP based Controller, Power Converter.

H_1, H_2, H_3 are position Sensors which sense the rotor position.

The rotor position information is fed to DSP based Controller which inturn supplies gating signals to the power Converter by turning on and off of the proper Stator pole windings of the machine. This makes the Torque & Speed of the machine a ease Control.



Block dia of Torque control of BLDC motor.



- The current controller & commutation sequencer provides proper gatting signal to 3ϕ inv

⑦ Switched Reluctance Motor (SRM) Drives.

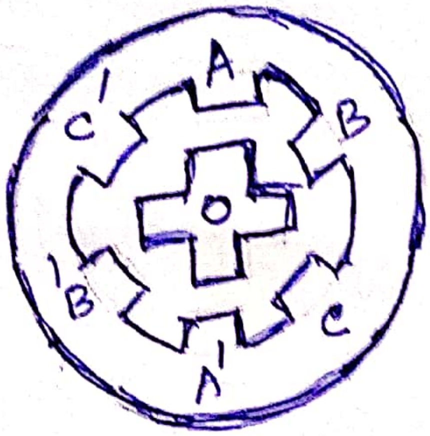
- Suitable as variable speed motor drive due to its low cost, rugged structure reliable converter topology, high efficiency over a wide speed range & control simplicity.
- It has no PM or winding in the rotor so high speed operation is capable when compared with Induction & PM machines
- SRM has a reliable inverter topology.
- A conventional SRM drive system consists of SRM, Power inverter, sensors like voltage, current & position & control circuitry such as DSP control & its peripherals.

Basic Structure:

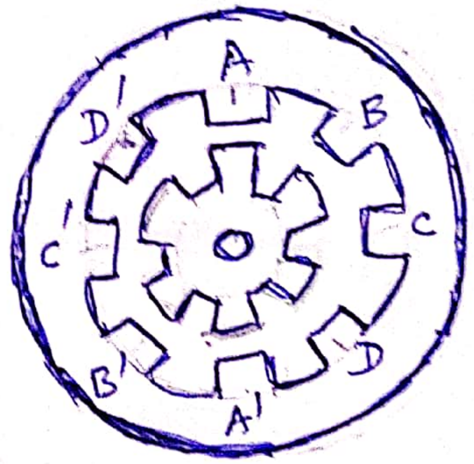
- SRM has salient poles both in the stator & rotor
- It has concentrated windings in the stator & no winding or PM in the rotor

The Configuration of SRM depends on the number & size of the rotor & stator poles.

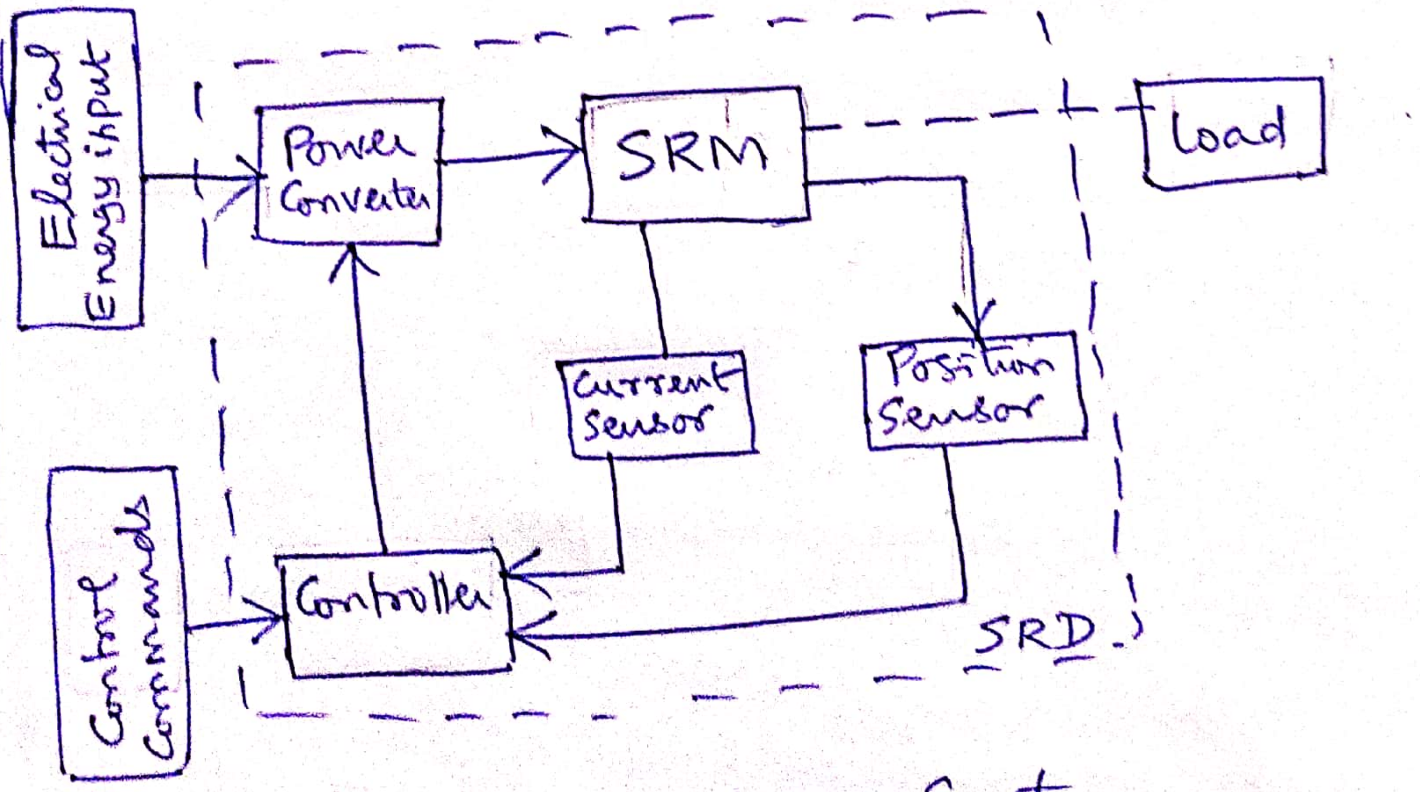
8/6 and 6/4 SRM are more Common.



6/4 SRM



8/6 SRM



SRM Drive System

- In the design practice and due to its double saliency structure, the reluctance of the flux path for a phase winding varies with the rotor position.
- Since the SRM is commonly designed for high degree saturation at high phase current, the reluctance of the flux path also varies with the phase current.
- As a result, the stator flux linkage phase bulk inductance and phase incremental inductance all vary with the rotor position & phase current.
- In order to ensure winding commutation & self-start capability at any rotor position & either rotating direction, there should be a small overlap between adjacent stator and rotor salient poles when the axis of the stator pole is aligned with that of rotor pole. ∴ the width of the rotor pole is usually larger than that of stator

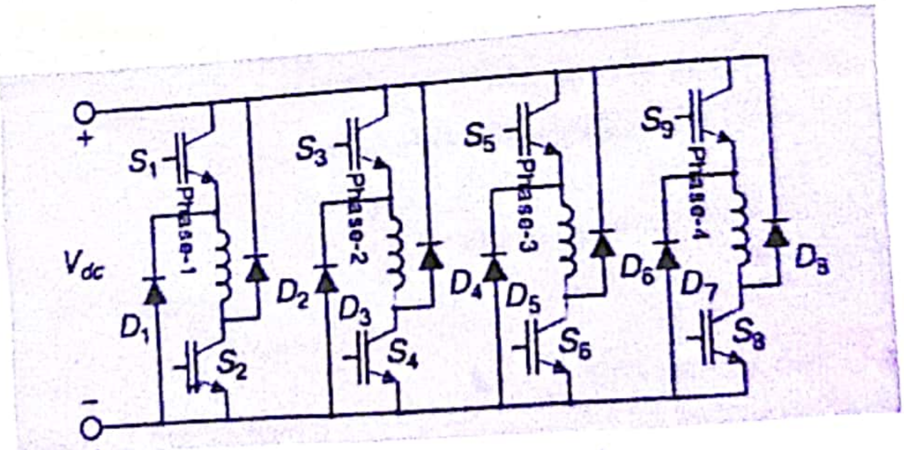
- At a fixed phase current, as the rotor moves from the unaligned to the aligned position, the reluctance of the flux path reduces due to the reduction in the airgap. As a result the phase inductance & flux linkages increases as the rotor moves.

- At a fixed rotor position, as the phase current increases, the flux path becomes more & more saturated. So the reluctance of the flux path reduces as the phase current increases. As a result, the phase bulk inductance drops with an increase in the phase current. But the phase flux linkage still increases as the phase current increases due to enhance-ment in the excitation.

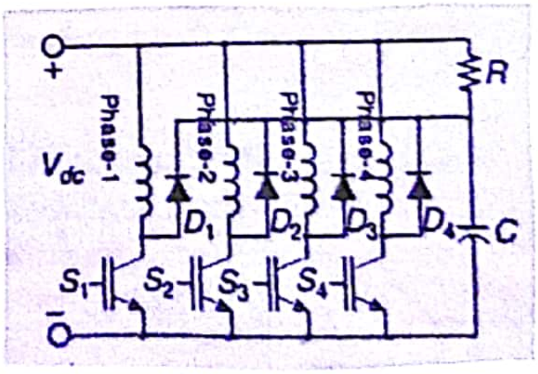
Torque in SRM is produced by the tendency of the rotor to get into allignm-ent with the excited stator poles.

- In order to produce positive torque (motoring torque) the phase has to be excited when the phase bulk inductance increases as the rotor rotates.
- Negative torque is generated if the phase is excited when the phase inductance is dropping as the rotor moves.
- The torque developed by the motor can be controlled by varying the amplitude & the timing of the current pulses in synchronism with the rotor position using certain type of inverters.

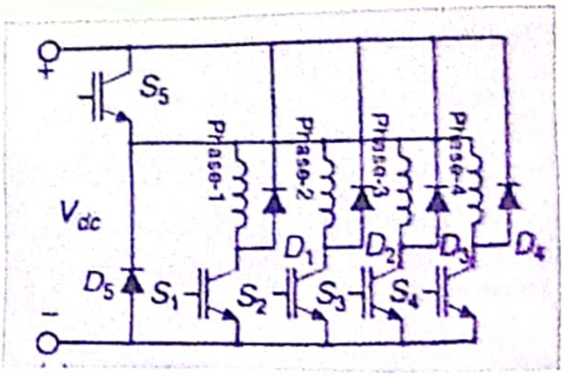
Different Inverter topologies for SRM drive



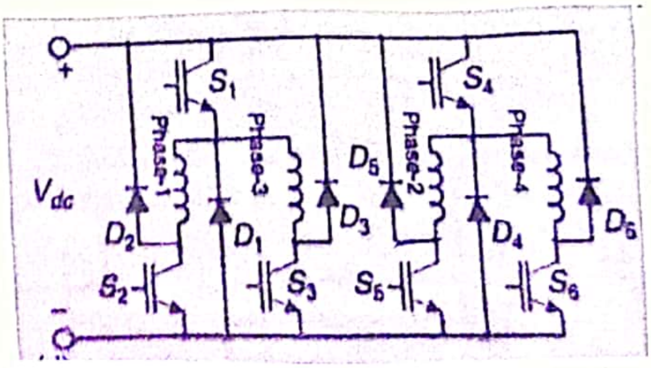
a) classical half bridge converter



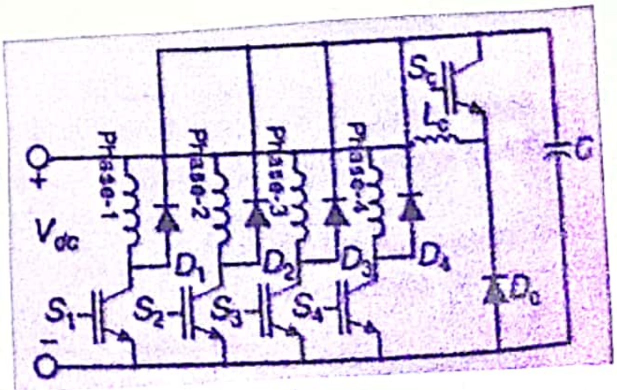
b) R-dump



c) Miller Converter
(n+1) switch
Converter



d) 1.5n switch
Converter



e) C-dump.

Basic configuration of PM motor drives.

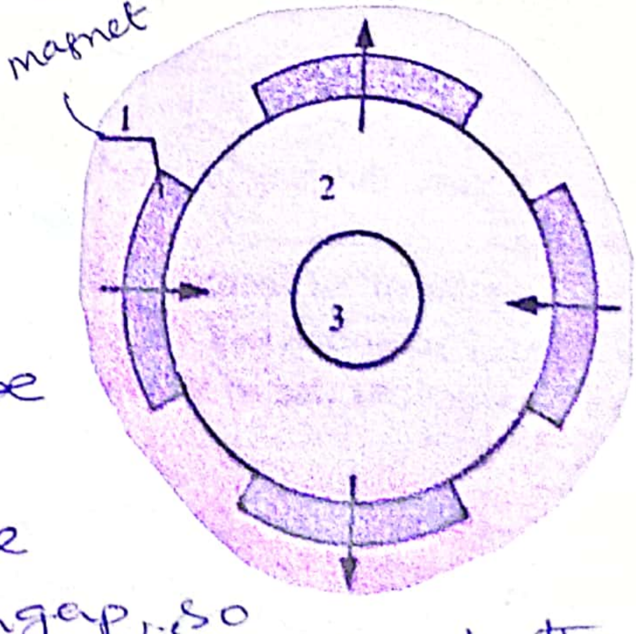
- When PMs are used to generate magnetic field in an elec machine it becomes PM motor.
- Both DC & AC motors can be made with PM.
- PM syn motor & PMBLDC used for traction drive.
- PM syn motor consists of rotor & stator with stator similar to that of Induction

motor but rotor Consists of PM.

- Similar to 3ϕ Ind motor, to generate a constant average torque, the rotor must follow the stator field and rotate at the same syn speed.
- That is why this machine is called PM Syn motor.
- There are different ways to place the magnets on the rotor.

Surface Mounted PM motors (SPM)

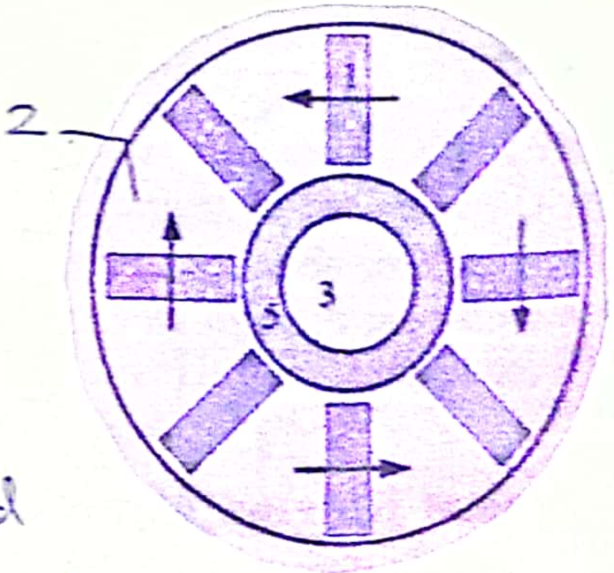
iron core.



- If the magnets are glued on the surface of the rotor it is called SPM.
- In this the rotor can be a solid piece of steel since the rotor iron core is not close to the airgap, so eddy current & hysterisis losses due to the slot/tooth harmonics can be neglected.
- Due to large air gap as well as the fact that the magnets have permeability similar

to that of air SPM motors have similar X_d and X_q.

Interior PM motors :



1 - magnet
2 - iron core
3 - Shaft
4 + 5 - non magnetic material.

- If the magnets are inserted inside the rotor in the pre-cut slots than it is called Interior PM or IPM motor.
- In this rotor needs to be made of laminated Silicon Steel as the tooth/slot harmonics will generate eddy-current & hysterisis losses.
- IPM have different X_d and X_q. This diference generate reluctance torque. This doesn't mean high torque rating than SPM for the same size & same amount of magnetic material used (as the reluctance torque is of ZigZag nature So SPM have higher total flux)

(10) Configuration of IPM motors.

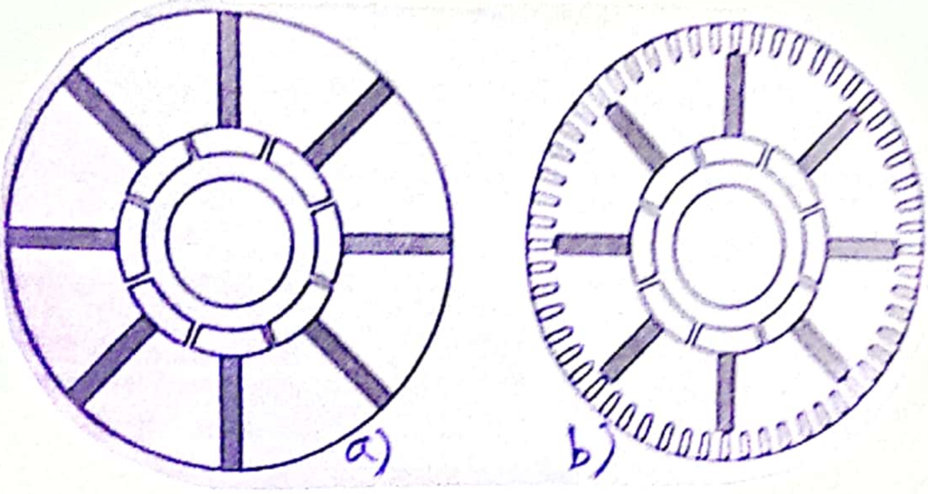
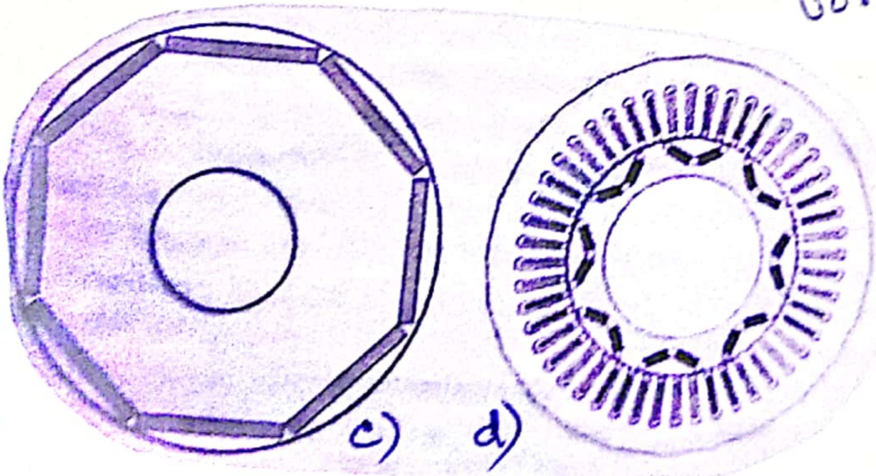


fig a) Circumferential type PM for BLDC (or) Syn motor.
b) Circumferential type PM for Syn motor.



c) Rectangular slots IPM motor
d) V type slots for IPM motor.

- Air gap flux is one of the most important Parameters of PM motor design generally the equivalent magnetic circuit analysis is used to Calculate the airgap flux in PM.
- In SPM equivalent circuit analysis is straight forward but in IPM motor

as the PMs are burried inside the rotor lamination with magnets inserted into the pre-stamped slots. The arrangement protects the magnet from flying away from the rotor surface due to the centifugal force, fatigue & aging of material during motor operation.

- Another advantage of IPM motor is that rectangular (Cuboid) magnets can be used to simplify the manufacturing process & reduce the manufacturing cost.
- Flux concentration structures (such as magnets arranged in V-shape) are often used to increase the airgap flux density in IPM motor.

PM motor disadvantages:

- Faces the possibility of demagnetization at extremely high temperature, limited speed range, difficulty in protecting the powertrain during fault condition.

- Ind motors have limited torque capabilities at low speed, lower torque density, low efficiency, noise due to stator/rotor slot combinations & so on.

Note SRM are similar to syn motor but will have different number of poles on the stator & rotor.

— x —

Doubly Salient PM machines (DSPM)

- This is a new kind of inverter-fed electric traction motor proposed in early 1990s.
- DSPM machine has structure like SRM except that PM are inserted in stator.
- DSPM has high efficiency, high power density & simple structure.
- Few common techniques used for SRM can also be adopted for DSPM

- wider rotor pole arc, advanced shut off angle control, lagged firing angle control can be used in the design & control of DSPM machines.
- As PM is in the stator the behavior of DSPM machine is different from that of SRM.
- Stator PM flux play a major role in the winding flux linkage so dual polarity control can be employed to improve the power density.
- |||^r to SRM to ensure winding commutation & self start capability at any rotor position & either rotating direction there should be a small overlap between the adjacent stator & rotor salient poles (width of rotor poles usually larger than stator poles)

- Even though structural similarity exits between DSPM & SRM motors, there exists a Cogging torque due to the PM in the stator, which is an important issue in DSPM motors. This Cogging Torque in DSPM motors reaches its minimum value if the resultant gap reluctance is uniform at any rotor position.

For 6/4 pole pared DSPM

- If width of rotor pole = stator pole width & width is one-half of the pitch, then Cogging torque will reach its minimum value.
- If the rotor pole width is > than stator pole width, the cogging torque will increa significantly because the gap reluctan -ce will not be uniform as the rotor position varies.

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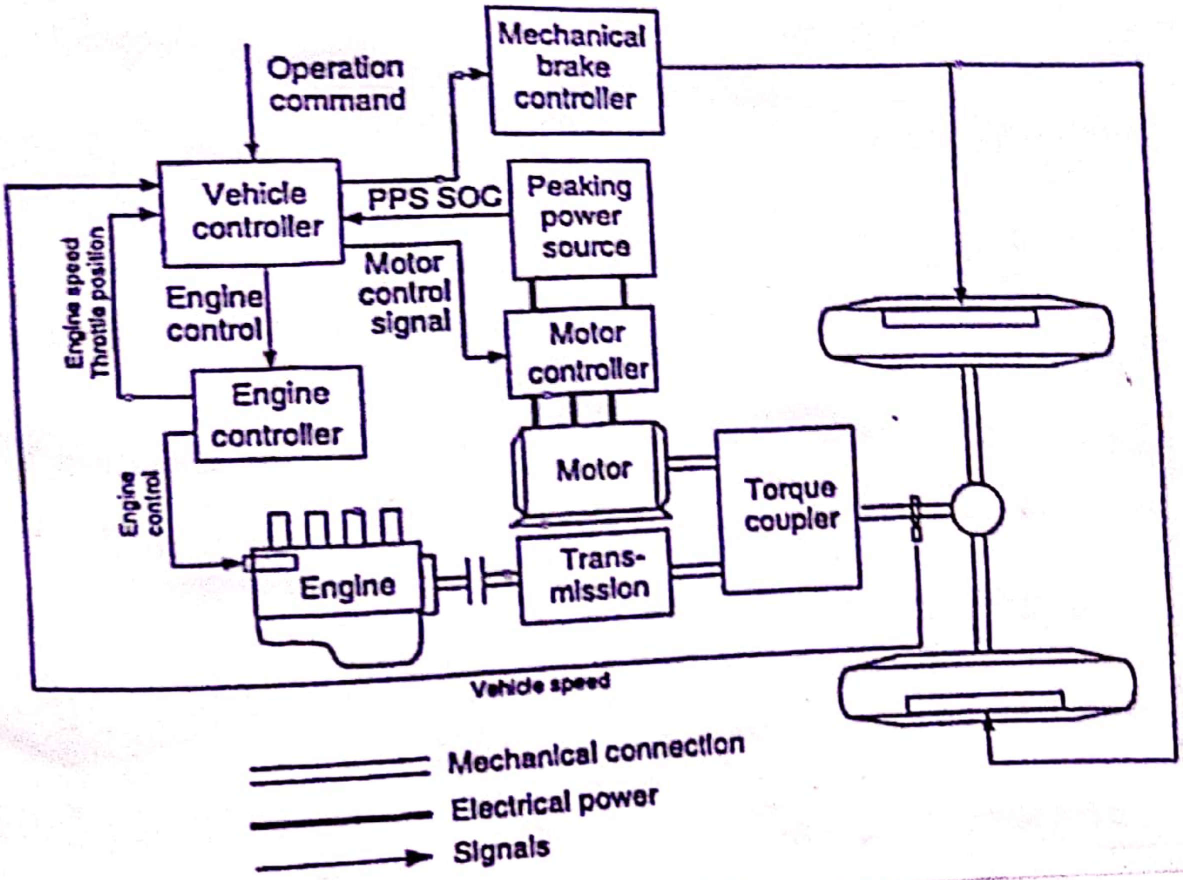


Fig. Configuration of the parallel torque-Coupling Hybrid drive train

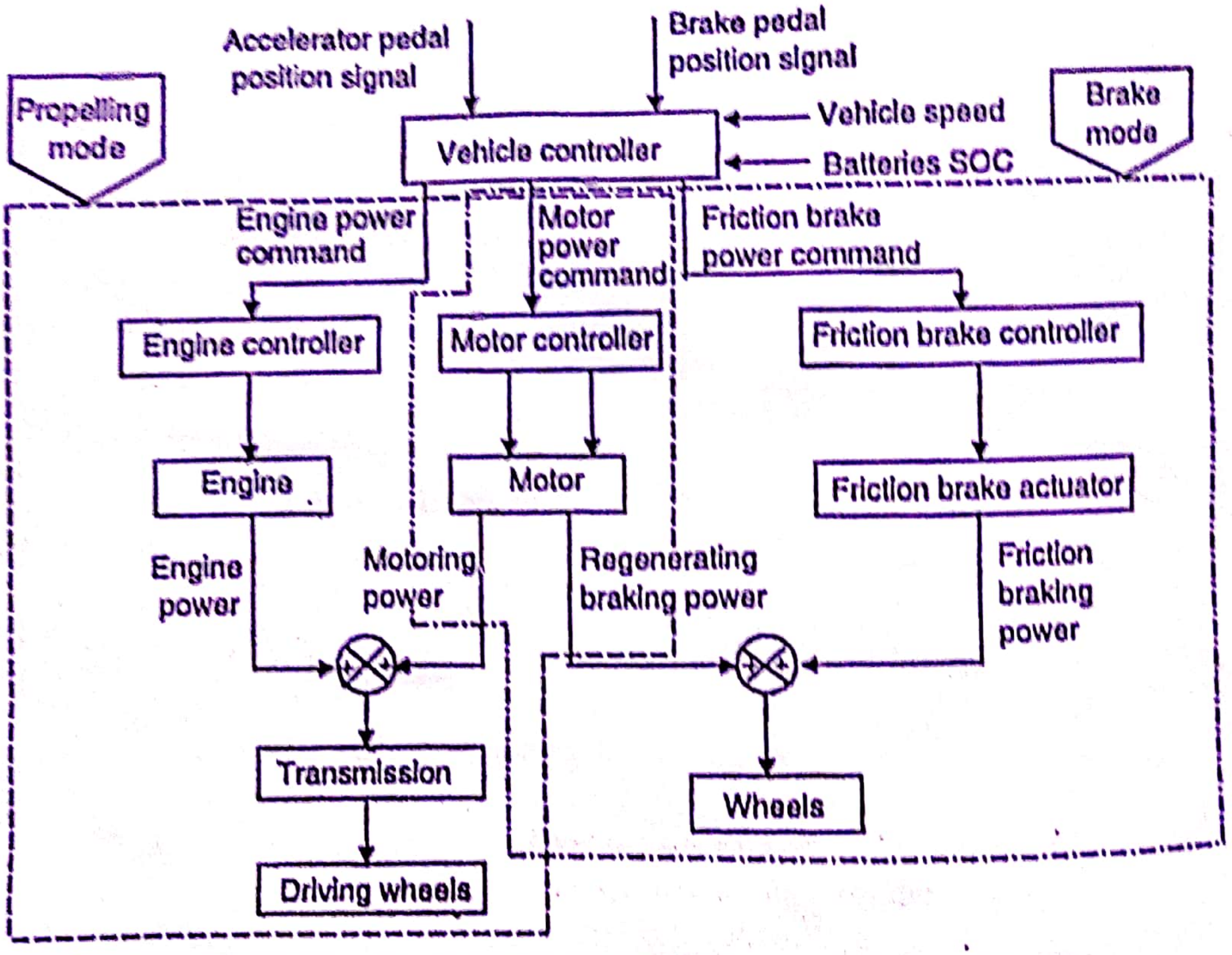


Fig. overall control scheme of the parallel hybrid drive train.

① UNIT IV

Energy Storage :- Introduction to Energy Storage (ES) requirements in Hybrid & Elec Vehicles. Battery based ES & its analysis Fuel cell based ES & its analysis - Super-Capacitor based ES & its analysis - Flywheel based ES & its analysis - Hybridization of different ES devices - Sizing the drive system - matching the elec machines & ICE, sizing the propulsion motor, sizing the Power Electronic, selecting the ES techno-logy, Communication & supporting systems

Dr.I.A.Chidambaram Ph.D
Professor, EEE Dept.

— × —

- In HEV or Plug-in HEV, on board batteries (or) Ultra Capacitors are charged from ICE / gen set or from electrical grid.
- In batteries the chemical energy stored is converted into electrical energy for traction motor & vehicle propulsion. So the performance of EVs & HEVs depends

Energy Storage Systems (ESS) to a large extent.

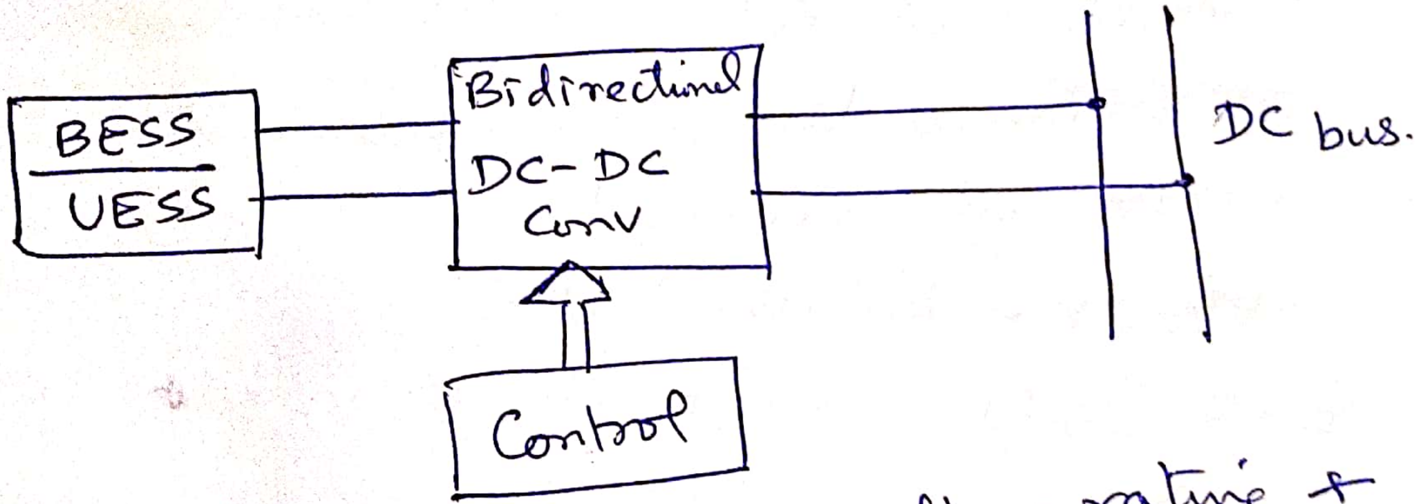
① Batteries (BESS)

- They are made of cells where chemical energy is converted to electical energy & vice versa.
- BESS comprises batteries, Power electronics based conditioning system & control system.
- With bidirectional capabilities battery provides energy for traction motor & store regenerative energy.
- Power Electronics provides an interface between battery & power producing on-board ICE unit (or) utility power unit in case of plugged-in Hybord Elec Vehicles (PHEV)
- Control system is responsible for power & energy management including charging/discharging & equalization control.

Ultra Capacitor based ESS (UESS)

UESS also have the above three units. But UESS doesnot involve any electro Chemical reactions

BESS/UESS Topology:



- To have the desired voltage rating + current rating for HEV applications may cells must be connected in series and/or in parallel in BESS or UESS.
- voltage balancing or equalization is required if more than 3 cells are connected in series.
- A battery has the characteristics of high energy & relative low power density.

- One internal resistance is the major factor to its limited discharging & charging current capability
- In this, the Internal Equivalent Series Resistance (IESR) has different values under charging & discharging operating condition & the values are also dependent on the frequency of discharging current.

example For Lithium battery

IESR could increase by 50%. from 1000 Hz to 100 Hz

- The ampere-hour capacity is affected by the discharging current rate & is modelled by Penkert's equation

$C_p = I^K . t$ where K is Penkert constant (K = 1 for an ideal battery)

- The charging & discharging efficiencies are nonlinear function of current & SOC. (State of Charge)

Battery modelling

with internal resistance model

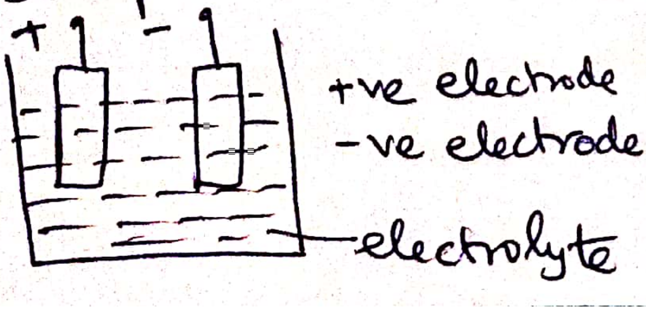
- Here battery modelled as a voltage source & an internal resistance are functions of SOC & Temperature.

With Resistance--Capacitance (RC) model.

- Battery is represented as a parallel Combin-ation of two R-C branches.
- Very large Capa models for the battery's Charging & low Capa model the time Constant limits the current.

- When Compared to ordinary Capacitor, Ultra Capacitor (Two layer capacitor (or) Super Capacitor) have Very high energy density almost thousands of times greater than a high capacity electrolytic Capacitor.

- Electro Chemical Batteries are Commonly referred as Batteries
- A battery is Composed of several Cells stacked together.
- A Cell is an independent & Complete unit that possesses all electrochemical properties.
- Basically a battery cell consists of three primary elements (+, -ve) electrodes, immersed into an electrolyte.
- Batteries are usually specified with Coulometric Capacity (amp-hr) which is defined as the number of amp-hr gained when discharging the battery from a fully charged state until the terminal voltage drops to its cut off



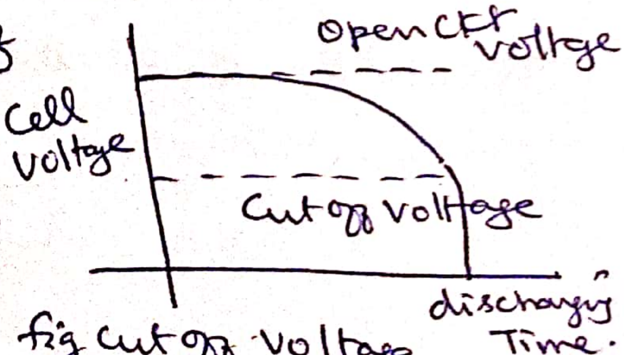


fig cut off voltage

$$\Delta SOC = \frac{i\,dt}{Q(i)}$$

$Q(i)$ → amp hr. capacity of battery at current rate i

$$SOC = SOC_0 - \int \frac{i\,dt}{Q(i)}$$

SOC_0 ↑ initial value of SOC

i is +ve for discharging, −ve for charging

Energy delivered from battery is referred as Energy capacity

$$= \int_0^t V(i, SOC) \cdot i(t)\,dt$$

V ↑ voltage at battery terminals

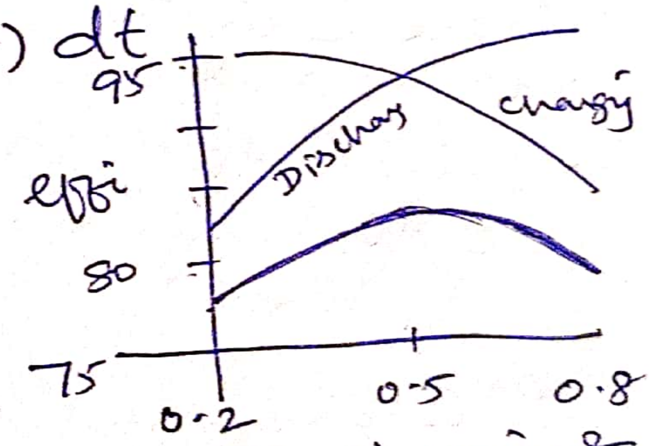


fig: Typical battery charging & discharging efficiency.

Battery characteristics:

Capacity: This specifies the amount of elec charge that can supply before it is fully discharge

Unit: Coulomb; general unit ampere-hour with
1 Ah = 3600 C

example: A battery of 20Ah Can supply 1A of current for 20hrs (or) 2A for 10hrs.

- Battery Capacity is dependent on its discharging rate.

There are two ways to indicate the battery discharge rate

$C_p = nC$

where C is the rate in amperes

nC is the discharge rate (i.e discharges in $1/n$ hours)

eg $C/5$ represents battery discharges in 5hrs.

5C represents battery discharges in 0.2hrs.

$C_p = I^k t$

where K = Penkert Constant

For Lead Acid battery K = 2 to 1.05 depends on manufacturing technology

For 2 Ah battery the $C/5$ rate is 400mA while 5C rate is 10A.

② Energy Stored (E) in a battery:

- This depends on the battery voltage and the amount of charge stored within

Unit : Watt hour (or) Whr (or) Wh

$$E(\text{Whr}) = \underset{\uparrow \text{ voltage}}{V} \cdot C \nwarrow \text{capacity in Ah}$$

State of Charge (SOC):

- It is a measure of residual capacity of a battery

Electric charge that a battery can hold

is $\int_{t_0}^{t} I_b(t)\,dt$

Total charge that a battery can hold

is $Q_0 = \int_{t_0}^{t_2} \underset{\uparrow \text{ charging current}}{I_b(t)}\,dt$

where t_2 is the cut off time when the battery no longer gets charged

$$SOC = \frac{\int_{t_0}^{t} I_b(t)\,dt}{Q_0} \times 100\,\%$$

ranges 20 to 95%.

- It is to be noted that SOC should not fall below 40%.

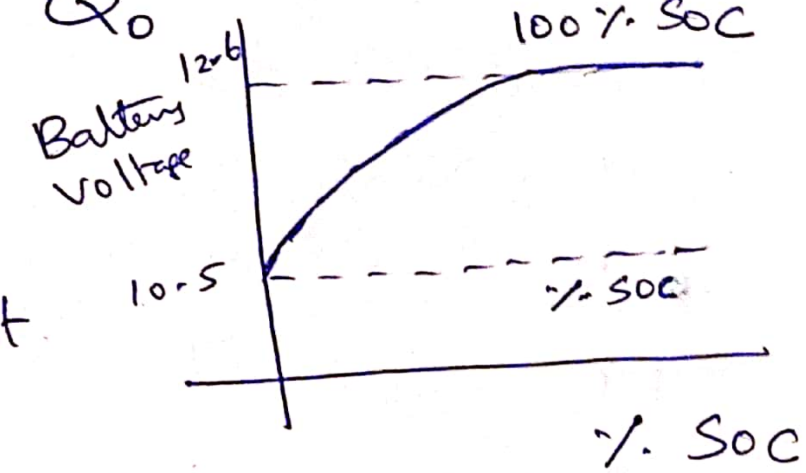


fig. example for 12ⓑ

Depth of Discharge (DOD):

- It is the % of battery capacity to which the battery is discharged.

$$DOD(t) = \frac{Q_0 - \int_{t_0}^{t} I_b(t)\,dt}{Q_0} \times 100\,\%$$

Generally battery is prevented from having low DOD.

Withdrawal of at least 80% of battery capacity is regarded as a deep discharge.

Note . The charge in a battery should never be discharged to zero voltage, otherwise battery will be permanently damaged. So a cutoff voltage level has to be ensured and referred as 100% DOD.

Energy density:

This is how much electrical energy that can be stored per cubic meter of the battery volume.

Unit : Whr/m^3

Specific Energy:

This is how much electrical energy that can be stored per unit mass of the battery

Unit : Whr/Kg.

Note: Specific Energy is not a constant parameter as the energy stored varies with discharge rate.

Energy Source	Specific Energy Wh/Kg
Gasoline	12300
Natural Gas	9350
methanol	6050
Hydrogen	33000

Coal	8200
Lead Acid Battery	35
Nickel Metal Hydride Battery	50
Lithium Polymer Battery	200
Lithium-ion Battery	120
Flywheel (Carbon fiber)	30
Ultra Capacitor	3.3

Specific Power & Power density

Specific Power: It is the ability of the battery to supply energy (or) how much Power that can be supplied per kg of battery.

High Specific power indicates that it can give & take energy quickly.

Power density (or) Volume Power density
It indicates the amount of Power per unit volume of the battery.

If a battery has high specific energy & low specific power it means the battery stores lot of energy, but gives it slowly.

Charge efficiency (or) Ampere hour

$$= \frac{\text{Electrical charge given out during discharging}}{\text{Electrical energy needed for the battery to return to the previous charge level.}}$$

Typical charge efficiency range 65 to 90%.
This depends on the battery type, temperature, & rate of charge.

Energy Efficiency :

- This is the important quantity indicating the energy conversion efficiency of the battery which mainly depends on the internal resistance

$$= \frac{\text{Electrical energy supplied by the battery}}{\text{Amount of charging energy required for the battery to return to its previous SOC before discharging.}}$$

Ragone plot is used to depictch the relation between Sp. Power & Sp. Energy

- This decreases if the battery discharged & charged very quickly.
  Typical value is 55 to 95%.

Number of deep cycles & battery life:

EV/HEV battery can undergo a few hundred deep cycles to as low as 80% DOD of the battery. This affects the battery life also.

Different types of batteries have different number of deep cycles.

United States Advanced Battery Consortium has a mid-term target of 600 deep cycles for EV batteries.

Main factors affecting the range of EV
- Driver's habit → Smooth driving gentle acceleration
  → minimal braking
- Use of Air conditioners
- Cold weather.

End of battery life when the battery capacity drops to 80% of its rated capacity.

Lead Acid Batteries (LAB) ($P_b - P_bO_2$)	Alkaline Batteries Nickal based (Ni-Cad, Ni-Fe, Ni-MH)	Lithium based Batteries (LB)
by Gaston Plante - French Physists 1859 • Uses an aqueous solution of Sulphuric acid ($2H^+ + SO_4^{2-}$) as electrolyte • Electrodes are made of Porous lead(P_b) anode electrically negative & - Porous lead oxide (P_bO_2, Cathode electrically positive) LA batteries are commercially	Nickel is lighter metal than lead & has a very good electro chemical properties for battery application There are 4 different kinds of battery technologies Nickel iron, Nickel Zinc Nickel Cadmium & Nickel metal Hydride. Nickel-Iron system (or) Edison battery • Commercialized during early years of 20th Century • Used in mine locomotive	Lithium is the lightest of all metals. • This allows a very high thermo-dynamic Voltage results in very high specific energy & specific Power. Two major Technologies are available. Lithium -Polymer Lithium -ion

Sucessful more then 150 years & still widely used as ESS in EV & other applications.

<u>AdV</u>

- High Power capability
- Low cost
- Matured technology
- Good cycle.

<u>DisadV</u>

- Energy density is low (because of high molecular weight of lead)
- Temperature Characteristics is Poor.

railway locomotives motorized hand trucks Shuttle vehicle.

Comprises of Nickel hydroxy oxide (NiOOH) as Positive electrode metallic iron as negative electrode Potassium Hydroxide (Contains Lithium hydroxide) as electrolyte

Normal Open circuit voltage <u>1.37V</u>

<u>AdV</u>

- High Power density Compared to LA batteries &

Capable of withstanding 2000 deep discharges.

① Lithium Polymer (Li-P) battery

uses Lithium metal as negative electrode Transition metal Intercalation Oxide (M_yO_z) for positive electrode.

Thin Solide Polymer Electrolyte (SPE) is used which offers improved safety & flexibility in design.

On discharge Lithium-ion formed at negative electrode migrate through SPE & are inserted into the crystal structure at positive electrode

LA Battery	Nickel based battery	Lithium based battery
• Below 10°C its sp. power & Sp. energy are greatly reduced. (Cold Climates) • Corrosive Sulfuric acid is hazard for Vehicle occupants • Hydrogen (extremely flammable) released by the self discharge reaction is another Potential danger. (even in hermetically sealed battery) • Pressure builds up as to keep trapping the parasitic gases	**Disadv** • Corrosion, gas outlet Self discharge Complex as it needs to maintain water level. • Proper disposal of Hydrogen & Oxygen during discharging Process. • Suffers from low temperature although less than LA batteries • Cost higher than LA batteries. ↓	on charging, the Process is reversed. Li foil as negative electrode Vanadium Oxide (V_6O_{13}) as Positive electrode is more advanced operates at normal Voltage of 3V. • Sp. energy 155 Wh/kg • Sp. Power 315 W/kg **adv** • Very low self discharge (0.5%/month) • Safety design

in the Casing & Causing swelling & mechanical Constraints on Casing & sealing.

Sp. Energy 40Wh/kg

Sp. Power 285W/kg.

Long Cycle life (over 600 cycles for on-road EV appli)

Rapid rechargable Capability:-

50% capacity in 8 min

&

100% capacity in less than 30 min

Low cost (₹1,45,000-2,15,000)

Mechanical ruggedness

Nickel-Cadmium Battery

Here also Nickel Hydroxyoxide (NiOOH) as Positive electrode & Metallic cadmium as negative electrode

Performance similar to Nickel-iron battery

Nominal open circuit Voltage is 1.3V

AdV

Sp. power 220W/kg

Long cycle life (upto 2000 cycles)

Small voltage drop over a wide range of discharging currents

Rapid Charge capability 40 to 80% in 18 min

disadv

Relatively weak low-temperature Performance due to temperature dependance of ionic conductivity.

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Lithium-ion Battery.

- Most promising rechargeable battery from 1991.

Lithiated Carbon Intercalation material (Li_xC) for negative electrode instead of metallic lithium

Lithiated transition metal intercalation oxide ($Li_{1-x}M_yO_z$) for Positive electrode.

Maintenance - free Conduction (sealed battery technology) environment friendly Advanced LA battery like bipolar design & Micro tubular grid design used to minimize the disadvantage Sp. energy can be increased by reducing the inactive materials (like casing, seperators etc...) • Special design is ensured to absorb the parasitic release of Hydrogen & Oxygen. • This battery is used in low voltage vehicles	Wide operating Temperature (-40 to 85°c) Low discharge rate (less than 0.5% /day) negligible corrosion. • Donot suffer from overcharging because once the Cadmium oxide has changed to Cadmium no further reaction can take place. Disadv • high initial cost • Relatively low cell voltage & Carcinogenicity & environment hazards of Cadmium Two types ↓	Liquid organic solution (or) Solid Polymer as electrolyte On discharge Li-ion released from negative electrode migrates via electrolyte & received by positive electrode. On charging the Process is reversed. For positive electrode $Li_{1-x}CoO_2$, $Li_{1-x}NiO_2$ & $Li_{1-x}Mn_2O_4$ be used have the advantage: Cobalt type has high Sp. energy but high cost. Li-ion battery with

① Vented type

- High sp. energy but costly.
- Have flat discharge voltage profile.
- Superior high current rate + low temperature performance.

② Sealed type.

- Prevents build up of Pressure inside the battery. so no maintenance.

Nickel Metal Hydride (Ni-MH) Battery

- In market since 1992
- characteristic similar to Ni-Cad battery
- Nickel Hydro oxy oxide as positive electrode Metal hydride as negative electrode absorbs hydrogen
- Superior Sp energy than Ni-Cad battery & free from toxicity & carcinogenicity.

manganese based battery has low Cost, abundance & environment friendly.

$LiNiO_2$ simply called as Nickel based Li-ion battery has normal voltage of 4V;

Sp. energy 120 Wh/kg

Sp. Power 260W/kg.

For HEV application

Sp. energy 85 Wh/kg

Sp. Power 1350 W/kg

For EV application

Sp. Energy 150 Wh/kg

Sp. Power 420W/kg

- Nominal voltage 1.2V
- Sp.energy 65 Wh/kg
- Sp Power 200 W/kg.

Two types of metal alloys are used.

Rare earth alloys
Lanthanum Nickel (AB5)

Titanium & Zirconium (AB_2)

AB_2 have higher capacity than AB_5

This Ni-MH is still under development

Highest Sp.Energy 70 to 95 Wh/kg.

High Sp. Power (200 to 300W/kg)

- Environment friendly
- Flat discharge profile.

Disadv High Cost.

Note

one cell of Li ion battery can deliver 3.7V

Even two cells of Ni-MH battery can deliver only 2.4V

—x—

Li-ion Battery
fast Charging
1-3 hrs.
But
Ni-MH Battery
slow charging
10-12 hrs.

—x—

Double Layer Capacitor / Ultra Capacitor

(or)

Super Capacitor.

- These are electrochemical double layer capacitors that store energy as electric charge between two plates, metal or conductive, seperated by a dielectric, when a voltage differential is applied acrross the plates. (Like batteries SC work in dc).
- The energy/volume obtained is superior to that of capacitors (5 Wh/kg or even 15 Wh/kg) at very high cost but with better discharge time constancy.
- SC are very durable 8-10 years 95% efficiency ; 5% self discharge/day.
- SC (or) UC unlike conventional capacitors uses double layer to form a very large surface area to allow the storage

- Its equivalent internal resistance is decades lower than the battery thereby allowing decades of higher discharging/charging currents. Its overall round trip efficiency is higher than that of battery.
- Main advantage of UC is that its SOC is allowed to vary more widely & thus have longer life cycles. Its capability to provide high power bursts is ideal for HEV applications.
- $|||^{r}$ to battery UC can be modelled as an Internal Resistance or RC model only difference is UC's internal resistance for charging is typically same as for discharging.
- For acceleration & deceleration transient period the behaviour of battery/UC's voltage & currents are predicted with their time constants.

For HEV applications UC have the following advantages.

- **High Power density** : unlike batteries, UC can be charged or discharged at a very high current rate & the temperature of the electrodes heated by the current is the only limiting factor. (has even 5000 W/Kg power density)
- **Excellent cycle life** : can endure millions of charge/discharge cycles that makes it to capture all available regenerative energy in HEV
- **More Environment friendly**
- **High efficiency** : UC has low internal resistance; efficiency around 97%

Disadv Energy density is substantially lower than for batteries (generally $\frac{1}{10}$ th of the same size battery.

- There is low resistance to leaks, resulting in higher self-discharge rate.

ESS is required to have Sp. energy, Sp. power, efficiency, maintenance, cost, safety, user friendly in EV; In EV → Sp. Energy is the first Consideration
energy from ICE →HEV → Sp. Power is the first Consideration

④ Energy Sources for EV

EV use different types of Energy Sources (ES) to ~~store~~ store their power

- Batteries
- Fuel cells
- Ultracapacitors
- Flywheels.

Main requirements of ES

ES should have

- High Specific Energy & Energy Density,
- High Specific Power & Power Density
- Fast charging & deep charging capabilities
- Long cycle & service lives
- Low self discharging rate & high charging efficiency.
- Safety & Cost effective
- Maintenance free
- Environment friendly & recyclable

Requirements for EV batteries.

- Batteries should have
  - stable voltage output over a good depth of discharge
  - High energy capacity for the given battery weight & size.
  - High peak power output per unit mass & volume.
  - High energy efficiency.
  - Able to function with wide ranges of operating temperatures.
  - Ability to accept fast recharging
  - Ability to withstand overcharge & over discharge
  - Reliable in operation
  - Maintenance free
  - Rugged & resistant to abuse
  - Safe both in use & accident conditions
  - Made of readily available &

inexpensive materials with environmental friendliness.

- Efficient reclamation of materials at the end of service life.

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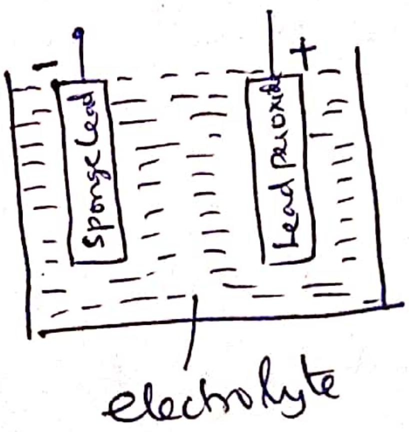
Lead Acid Battery (Pb

Positive plate → Lead Peroxide.

Negative plate → Spongy Lead

Electrolyte → Sulphuric Acid.



Adv

Reliable, Robust, Rapid recharging, tolerant to overcharging, low internal impedance, Can deliver high currents, Ability to hold the Charge over a period of not being used, Indefinite shelf life if stored without electrolyte, wide range of sizes & capacities available.

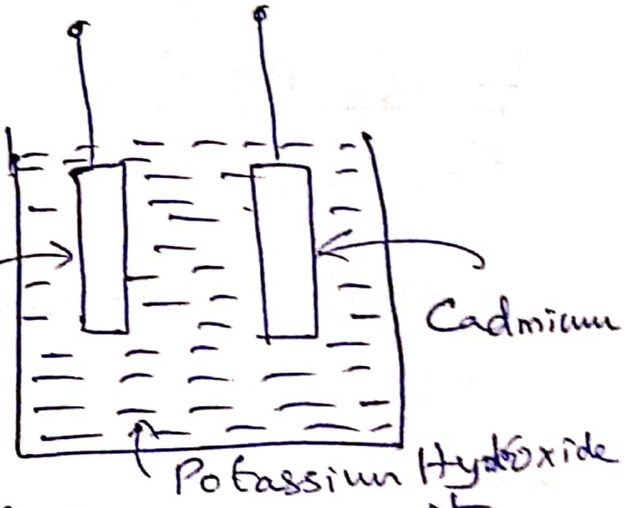
Disadv

Heavy & bulky, very low Specific energy, danger of overheating during charging, not suitable for fast charging

Typical cycle life 300 to 500 cycles; much be in charged state if electrolyte is introduced to avoid detoriation of active chemicals.

Acid fumes & corrosion, loss of voltage over discharge.

Nickel Cadmium Battery



- This is Alkaline battery.
- Ni-Cd battery used in EV even through Cadmium toxicity & nickel carcinogenity. (promotes Cancer)
- Life Span is not similar to Nickel-Metal Hydride (Ni-MH) batteries.

Positive plate → Nickel oxide Hydroxide ($NiOOH$)

Negative plate → Cadmium

Electrolyte → Potassium Hydroxide (KOH) & Water (H_2O)

(The electrolyte does not change during the reactions)

- This battery donot suffer from over-charging because once the Cadmium oxide has changed to Cadmium, no further reaction can take place.

- The cell voltage of a fully charged cell is 1·4V but this falls rapidly to 1·3V as soon as discharge starts. The cell is discharged at a cell voltage of 1·1V.
- The specific energy of NiCd battery is 30 to 50 Wh/kg which is similar to that of Lead-Acid battery.

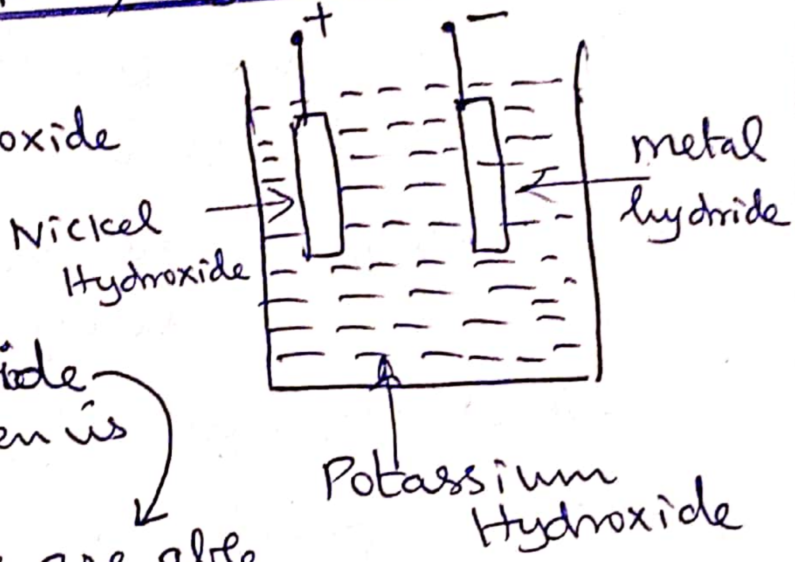
Adv

- Superior low temperature performance compared to Lead Acid battery, Flat discharge voltage Long life, excellent reliability, low maintenance

Disadv

- High cost, Toxicity due to Cadmium, develops insufficient power for EV and HEVs.

Nickel-Metal (Ni-MH) Hydride battery



Positive plate } → Nickel Hydroxide (|||^{r} to Ni-Cd) battery

Negative plate } → Metal Hydride where Hydrogen is stored

these are able to absorb & release hydrogen many times without deterioration.

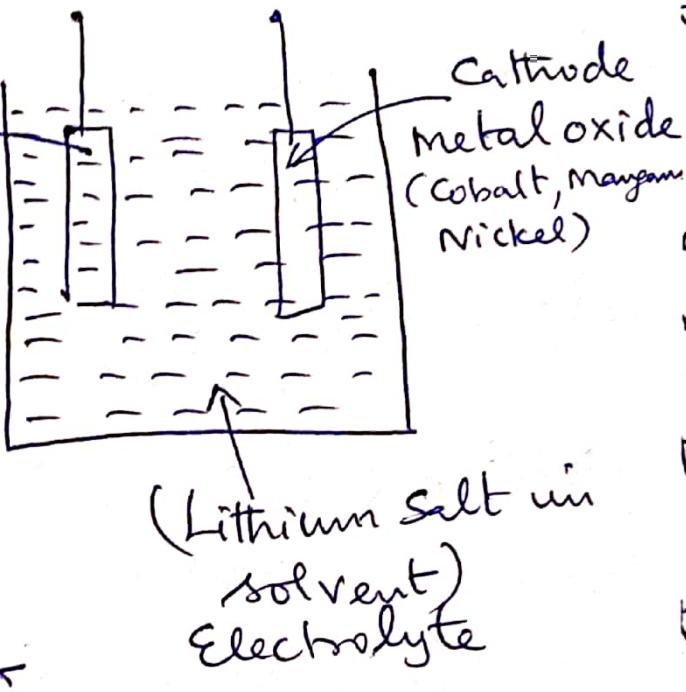
Adv

Charge up quickly, high cycle stability, 20% higher specific energy & power, longer life than Lead-Acid battery, Safe & abuse tolerant

Disadv

High cost, higher self-discharge rate compared to NiCd, low cell efficiency, at elevated temperature poor charging capability.

Lithium-ion Battery



Positive Plate Anode } → Carbon (graphite)

Negative plate Cathode } → Lithium metal oxide

Electrolyte → Lithium salt & an organic solvent

Adv

High Specific Energy & high Specific Power, upto 80% weight saving (lighter than LA battery ⇒ 3 or more times than the energy density of equal weight), charge & discharge at high currents, low self discharge, longer life span minimum 5 years Maximum 10 years depending on use, Li nontoxic so no harmful emissions, loss of Voltage over discharge

Disadv

High cost, more heat

Alternative Energy Storage Devices.

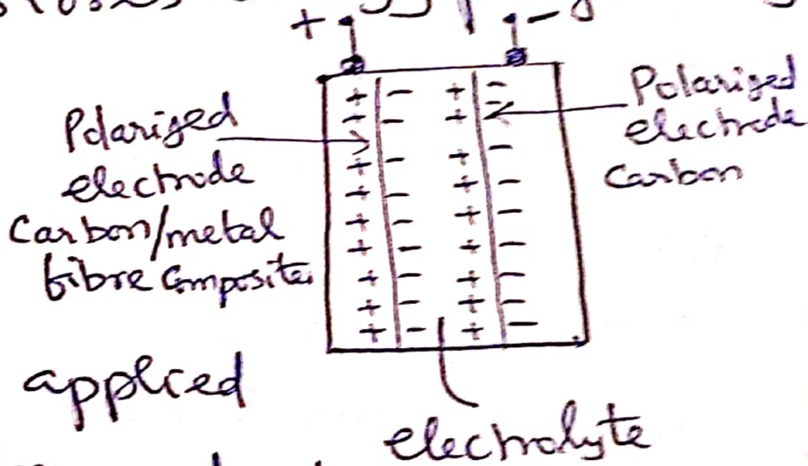
- Ultra Capacitor
- Flywheel.

Ultra Capacitor: (UC)

UC also known as Super Capacitor (SC) (or) Electro Chemical Capacitors.

Battery store their energy chemically but Ultra Capacitor stores energy physically.

- Double-layer capacitor technology is applied in UC.



- When a voltage is applied across the electrodes, a double layer is formed by the dipole orientation & alignment of electrolyte molecules over the entire surface of the electrodes.

$$C = \frac{\epsilon A}{d}.$$

- High dielectric materials are used which can seperate electrodes for short distance & large electrode surface areas

⑤ & so the Capacitance Can be greatly increased.

Electrode materials → Carbon/metal fibre Composites, doped conducting Polymer films on Carbon Cloth (or) Mixed metal oxide Coatings on metal foil

Electrolyte materials → Aqueous/organic solution (or) Solid polymer

- UC have little or no internal resistance down to 0 to 12 mΩ
- UC have lower Specific energy than batteries
- UC have much higher Specific Power but much lower specific energy Compared to Chemical batteries
- UC's Specific power can reach upto 5 kW/kg much higher than any type of battery.
- Because of UC's low specific energy density & dependency of Voltage on the

state of charge, it is difficult to use UCs alone as Energy storage for EVs & HEVs.

- UC technology is ideally suited to regenerative braking & start-stop systems.
  ↳ during traffic signal.

- UCs Power density is upto 60 times greater than batteries. This means it is Possible to recharge large banks of UCs in just 3 or 4 seconds.

Adv

- Can store 10 to 100 times more energy per unit volume or unit mass than standard electrolytic capacitor.
- Can be charged & discharged more quickly (almost instantly) than batteries.
- Tolerate many more charge/discharge cycles than rechargeable batteries.
- Provides large power surges for short Periods (time) without overheating.

- Deliver many times more power for weight than Lithium-ion batteries
- Have efficiencies upto 98%.
- Tolerates high temperature.
- Unlimited life cycle (over million cycles)
- one of the cheapest technologies for power discharges below 15 secs -

Disadv

- High capital cost, low maximum voltage, only about 1/10 the energy density of batteries.

— × —

Flywheel Energy Storage System (FESS)

- Flywheel is an energy storage system similar to battery, but instead of storing the energy chemically, it is stored in kinetic form in a rotating disc.
- FESS composed of composite rotors spinning at thousands of rpm on frictionless magnetic

bearings, which can drive a generator to power for EVs.

- Energy stored in Flywheels increases quadratically with the rotational speed of the rotors.
- Gyroscophic effect is avoided by having two adjoining Flywheels rotating in opposite direction at identical speeds on the stationary shaft.
- To reduce friction FW are made to rotate in Vacuum.
- Life of FW is very long & no replacement would be required when compared to chemical battery systems.
- FESS can be divided into

Low speed FW system
- This reduces air friction by increasing the mass of the FW.

High speed FW system
- This reduces the air pressure of operating environment of FW. Uses high strength Carbon Fibre.

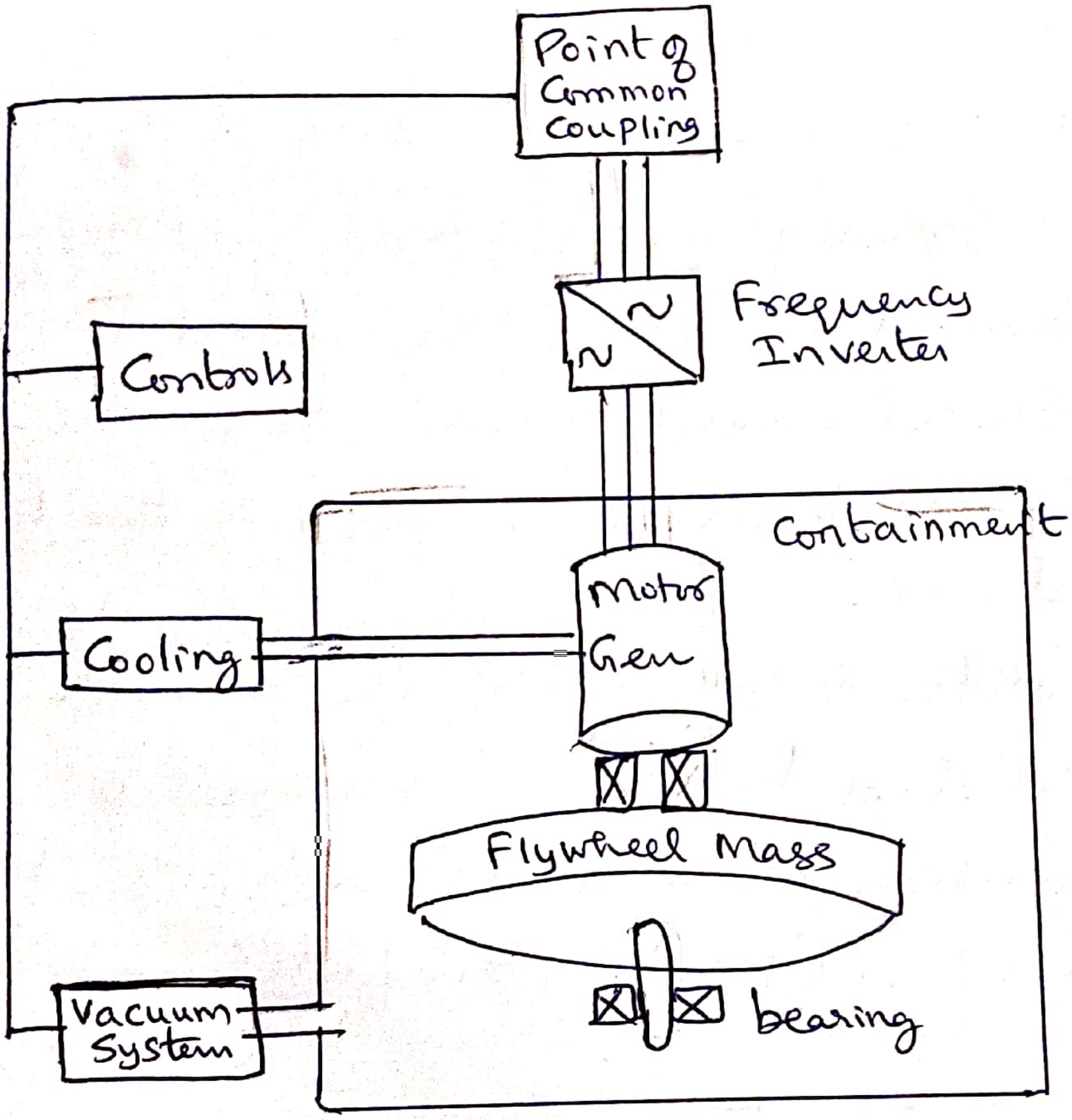


fig. FESS

- The high-speed FW system consists mainly of Flywheel (FW), a motor & a generator.
- It is connected with exterior electrical systems through input or output electronic equipments
- The power transported from exterior systems is converted from electrical

energy into mechanical energy by raising rotary speed of flywheel. (FW)

- When output power in required the mechanical energy is converted back to electrical energy through generator & meanwhile the rotary speed of the FW is reduced.
- The motor & generator are usually integrated together & magnetic suspension bearings are adopted by the Flywheel (FW) system fitted in Vacuum.

Adv

- High power density
- Long life cycle.
- No pollution
- No degradation over time.
- Easy estimation of State-of-Charge (SoC)
- Highest energy storage density
- Shortest Charging time
- Easiest Maintenance & No pollution

Disadv

- Excessive high cost
- Costs ⇒ about 1.5 times that of UC
  & about 6-7 times that of Chemical battery.

Comparison between battery, Ultra Capacitor & Flywheel.

	Battery	UC	Flywheel
Storage Mechanism	Chemical	Electrical	Mechanical
Life	3-5 years	1-18 years	> 20 years
Temperature range	Limited	Limited	Less limited
Energy with the mass	Large	medium	small
Time to hold the Charge	Months	days	Hours.

Company	Brand	Battery Type
Maruti	CiaZ	Li-ion
Suzuki	Scorpio Hybrid }	Li-ion
BMW	i3 & i8	Li-ion
Mahindra	Megapixel	Li-ion
TATA	Prius(PHEV)	NiMH
Honda	Civic Hybrid	NiMH
Toyota	Camry Hybrid	NiMH
Hyundai	i10 Electric	Li-Polymer

—x—

⑦

Basic technical requirements for a lead–acid cell in HEV/EV applications

Energy density	35–40 Wh/kg
Specific energy	60–75 Wh/L
Power density	150–200 W/kg
Round-trip energy efficiency	70–90%
Self-discharge rate	5–15%/month
Cycle durability	500–800 cycles
Nominal cell voltage	–2.1 V

Basic technical requirements for an NiMH cell in HEV/EV applications

Energy density	60–80 Wh/kg
Specific energy	160–200 Wh/L
Power density	240–300 W/kg
Round-trip energy efficiency	75–95%
Self-discharge rate	10–20%/month
Cycle durability	800–1000 cycles
Nominal cell voltage	–1.2 V

Basic technical requirements for a Li-ion cell in HEV/EV applications

Specifications	Unit	HEV application	EV application
Energy density (1C rate at 25 °C)	Wh/L	70–200	250–550
Specific energy (1C rate at 25 °C)	Wh/kg	50–100	150–230
Power density (10 second, at 50% SOC and 25 °C)	W/L	2000–9000	2000–4000
Specific power (10 second, at 50% SOC and 25 °C)	W/kg	1000–4500	1000–3000
Round-trip energy efficiency (1C rate at 25 °C)		92–97%	94–98%
Self-discharge rate (at 50% SOC and 25 °C)		<5%/month	<3%/month
Power/Energy (P/E) ratio (at 50% SOC and 25 °C)	hr^{-1}	25–50	10–25
Cycle durability		2000–4000 cycles	1500–3000 cycles
Nominal cell voltage	V	–3.75	–3.75

Characteristics of common Li-ion battery cathode materials

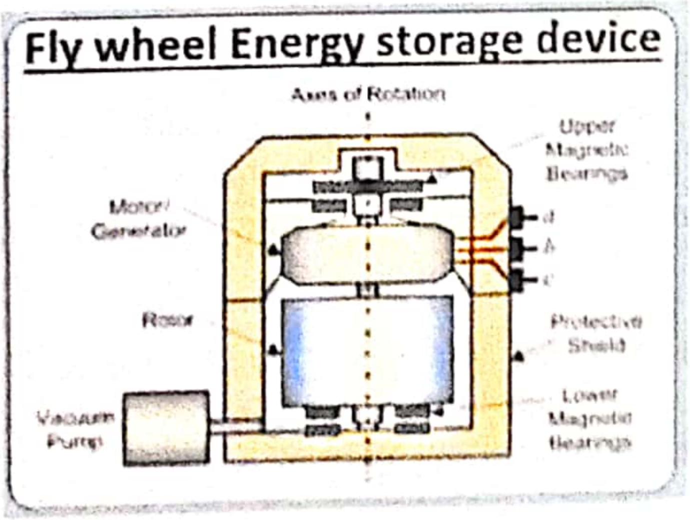
Structure	Compound	Average potential (V vs. Li^0/Li^+)	Specific capacity (mAh/g)	Specific energy Wh/kg
Layered	$LiCoO_2$ (LCO)	4.2	120–140	520–570
Layered	$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC)	4.0	160–180	610–660
Layered	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)	4.0	180–200	700–760
Spinel	$LiMn_2O_4$ (LMO)	4.1	100–120	420–500
Spinel	$LiMn_{1.5}Ni_{0.5}O_4$ (LMN)	4.7	100–120	460–520
Olivine	$LiFe_{0.5}Mn_{0.5}PO_4$ (LFP)	3.4	150–170	520–580

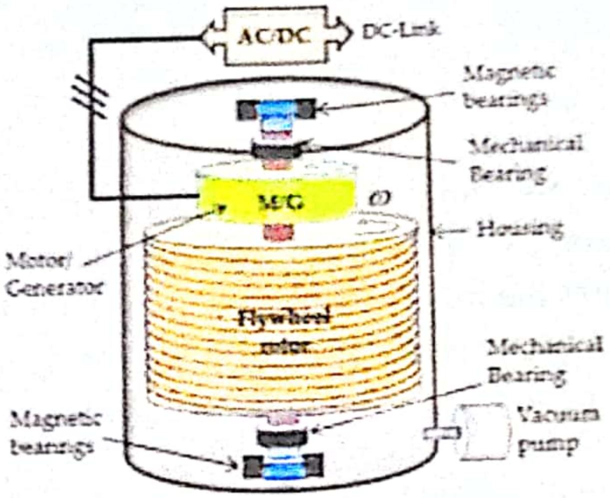
Advantages and disadvantages of common Li-ion batteries with different cathode materials

Compound	Advantages	Disadvantages
$LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC)	High energy capacity Slow reaction with electrolytes Ready SOC estimation Moderate safety (oxygen release)	High cost of Ni and Co Potential resource limitations Poor high rate performance
$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA)	Slow reaction with electrolytes High energy capacity High operating voltage Excellent high rate performance	High cost of Ni and Co Potential resource limitations Poor safety
$LiMn_2O_4$ (LMO)	Moderately low cost Excellent high rate performance High operating voltage No resource limitations Moderate safety (oxygen release)	Low cycle life due to Mn solubility issue Low energy capacity
$LiFe_{0.5}Mn_{0.5}PO_4$ (LFP)	Moderately low cost Excellent high rate performance No resource limitations Very slow reaction with electrolyte Excellent safety (no oxygen release)	Low operating voltage Low energy density Low power density Very challenged for SOC estimation

Flywheel

- **Flywheel Energy Storage Systems** (FESS) employ kinetic **energy stored** in a rotating mass with very low frictional losses. Electric **energy** input accelerates the mass to speed via an integrated motor-generator. The **energy** is discharged by drawing down the kinetic **energy** using the same motor-generator.
- **FESS** use electric **energy** input which is stored in the form of kinetic **energy**.
- To maintain efficiency, the **flywheel system** is operated in a vacuum to reduce drag. The **flywheel** is connected to a motor-generator that interacts with the utility grid through advanced power electronics.
- The Flywheel has 3 main functions. The first is to maintain a **rotating** mass (inertia) to assist the engine **rotation** and provide a more consistent delivery of torque during running. The second is to provide a ring gear for the starter motor to engage on.





- Flywheels are now made of a carbon fiber composite which has a high tensile strength and can store much more energy. The amount of energy stored in the flywheel is a function of the square of its rotational speed and its mass, so higher rotational speeds are desirable.

- FESS use electric energy input which is stored in the form of kinetic energy. Kinetic energy can be described as "energy of motion," in this case the motion of a spinning mass, called a rotor. The rotor spins in a nearly frictionless enclosure.

- When short-term backup power is required because utility power fluctuates or is lost, the inertia allows the rotor to continue spinning and the resulting kinetic energy is converted to electricity.

- Most modern high-speed flywheel energy storage systems consist of a massive rotating cylinder (a rim attached to a shaft) that is supported on a stator – the stationary part of an electric generator – by magnetically levitated bearings.

- To maintain efficiency, the flywheel system is operated in a vacuum to reduce drag. The flywheel is connected to a motor-generator that interacts with the utility grid through advanced power electronics components.

- Some of the key advantages of flywheel energy storage are low maintenance, long life (some flywheels are capable of well over 100,000 full depth of discharge cycles and the newest configurations are capable of even more than that, greater than 175,000 full depth of discharge cycles), and negligible environmental impact.

- Flywheels can bridge the gap between short-term ride-through power and long-term energy storage with excellent cyclic and load following characteristics.

- Typically, users of high-speed flywheels must choose between two types of rims: solid steel or carbon composite. The choice of rim material will determine the system cost, weight, size, and performance. Composite rims are both lighter and stronger than steel, which means that they can achieve much higher rotational speeds.

- The amount of energy that can be stored in a flywheel is a function of the square of the RPM making higher rotational speeds desirable.

- Flywheel energy storage systems (FESS) employ kinetic energy stored in a rotating mass with very low frictional losses. Electric energy input accelerates the mass to speed via an integrated motor-generator. The energy is discharged by drawing down the kinetic energy using the same motor-generator.

- The amount of energy that can be stored is proportional to the object's moment of inertia times the square of its angular velocity. To optimize the energy-to-mass ratio, the flywheel must spin at the maximum possible speed.

- Rapidly rotating objects are subject to significant centrifugal forces however, while dense materials can store more energy, they are also subject to higher centrifugal force and thus may be more prone to failure at lower rotational speeds than low-density materials. Therefore, tensile strength is more important than the density of the material. Low-speed flywheels are built with steel and rotate at rates up to 10,000 RPM.

- More advanced FESS achieve attractive energy density, high efficiency and low standby losses (over periods of many minutes to several hours) by employing four key features:

1. Rotating mass made of fiber glass resins or polymer materials with a high strength-to-weight ratio
2. A mass that operates in a vacuum to minimize aerodynamic drag
3. Mass that rotates at high frequency, and
4. Air or magnetic suppression bearing technology to accommodate high rotational speed. Advanced FESS operate at a rotational frequency in excess of 100,000 RPM with tip speeds in excess of 1000 m/s.

- Additionally, they have several advantages over chemical energy storage. They have high energy density and substantial durability which allows them to be cycled frequently with no impact to performance.

- They also have very fast response and ramp rates. In fact, they can go from full discharge to full charge within a few seconds or less.

- FESS are increasingly important to high power, relatively low energy applications. They are especially attractive for applications requiring frequent cycling given that they incur limited life reduction if used extensively

- FESS are especially well-suited to several applications including electric service power quality and reliability, ride-through while gen-sets start-up for longer term backup, area regulation, fast area regulation and frequency response.

- FESS may also be valuable as a subsystem in hybrid vehicles that stop and start frequently as a component of track-side or on-board regenerative braking systems.

Ultra High Speed Flywheels

(FW) or (FES)

- FW accumulators are Comprised of a massive or Composite flywheel Coupled with a motor-gen & special brackets (often Magnetic) set inside a housing at very low pressure to reduce self discharge losses.
- Have great Cycling Capacity (few 10000 to few 1,00,000 Cycles)
- For Energy storage high capacity flywheels are required.
- Friction losses of 200tons flywheel are estimated at about 200KW
- Instantaneous efficiency 85% & overall efficiency drops to 78% after 5 hours & 45% after one day. So long term storage with this FES is therefore not foreseenable
- Installation tended to be heavy & the gyroscopic forces of the FW are significant & Can over Come with Compact &

relatively light weight Carbon & steel flywheel.

- Flywheel can rotate at speeds upto 64000 rpm.
- Have high Sp. energy, high Sp. power, long cycle life, high energy efficiency, quick recharge, maintenance free, cost effective & environment friendly.
- Rotating FW stores energy in kinetic form as $E_F = \frac{1}{2} J_F \omega_F^2 \longrightarrow ①$

where J_F moment of Inertia of FW in Kgm^3

ω_F angular velocity of FW in rad/sec

- It is difficult to directly use mechanical energy stored in a FW to propel a vehicle with Continous Variable Transmission (CVT) & wide gear ratio variation range

→

⑥ Energy stored in FW $\propto J_F$

$\propto (\text{rotating Speed})^2$

- A light weight FW should be designed to properly achieve Moment of Inertia (J_F) per unit mass & per unit Volume.

$$J_F = 2\pi \rho \int_{R_1}^{R_2} W(r)\, r^3 \, dr.$$

$\rho \rightarrow$ material mass density

$W(r) \rightarrow$ width of the fw Corresponding to radius r

Power Capa of FW (P_F)

From eqn ①

$$P_F = \frac{dE_f}{dt} = J_F W_F \frac{dw_f}{dt} = w_f T_F$$

where T_f is the torque acting on the flywheel by motor.

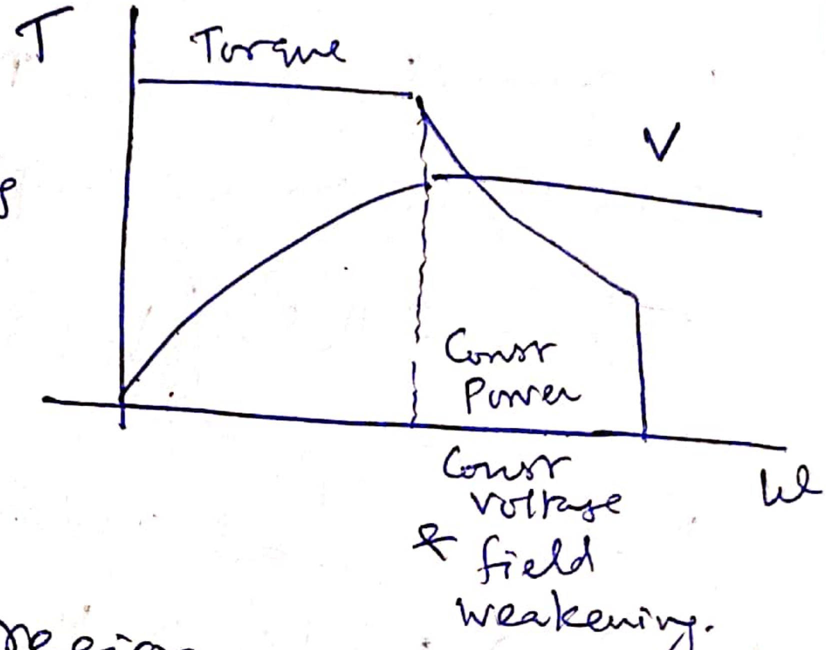
- When FW discharges its energy elec machine acts as a generator & Convert the mech energy of FW into elec energy.

- When FW is Charged, the elec machine acts as motor Converting elec energy to mech energy for Storage in FW

Elec M/c Charateristic has 2 distinct operating region.

- Constant Torque
- Constant Power

regions.



At Constant Torque region

The voltage of elec M/c ∝ angular velocity & magnetic flux in the airgap is Constant.

At Constant Power region

Voltage is Constant & magnetic field weakened with increasing m/c angular velocity

$$E_f = \frac{1}{2} J_f \omega_f^2 \Rightarrow E_f \propto (\text{Speed})^2.$$

Although high rotational speed can significantly increase the storage but limited by the tensile strength (σ) of the material constituting FW.

- Maximum benefit is obtained if the material have high $\left(\frac{\sigma}{\rho}\right)$ ratio.

sp. density (or) material mass density

- Due to the extreme speed & to reduce the aero dynamic loss & frictional loss the FW can be housed in a highly Vacuumed & noncontact, magnetic bearing are employed.
- In FW system PMBLDC, SRM motors are widely coupled for use.
- FW suffers from two specific Problems when used in EV & HEVs.

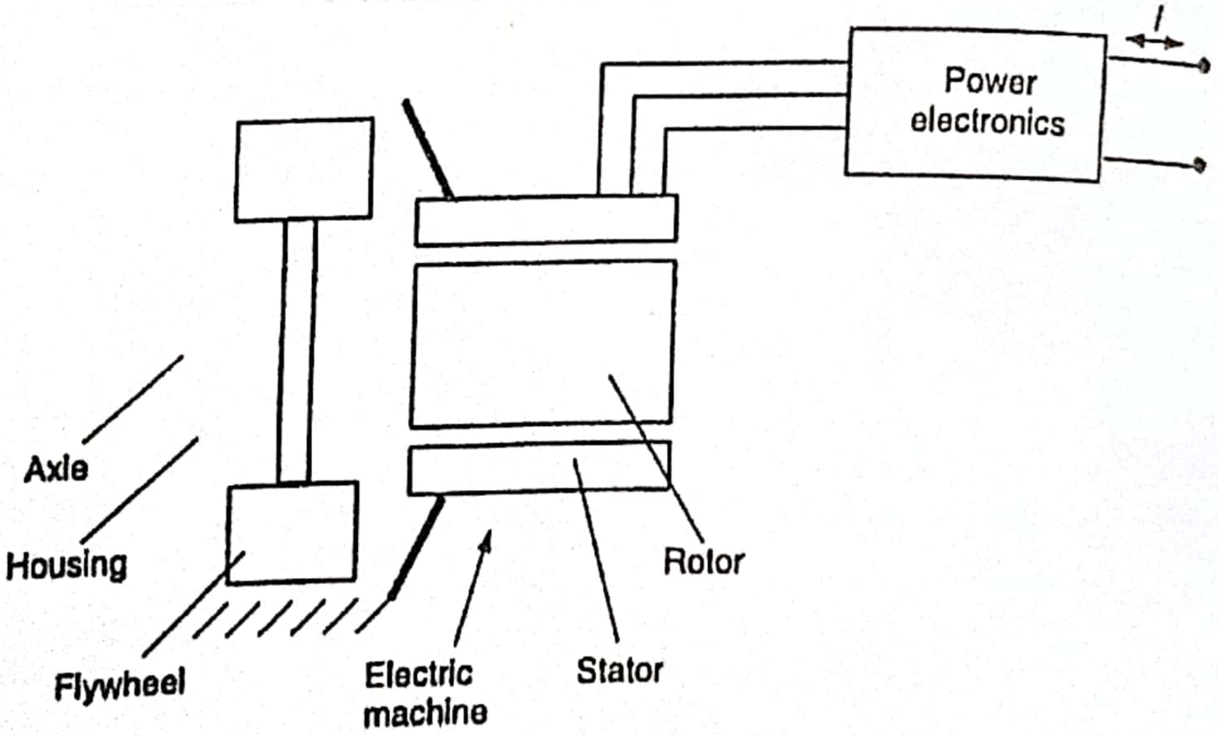
Gyroscopic forces occurs whenever vehicle departs from straight line (like turning & inpitching upward or downward from road grades,

If FW is damaged its stored energy in mech form will be released will be higher causing severe damage to vehicle

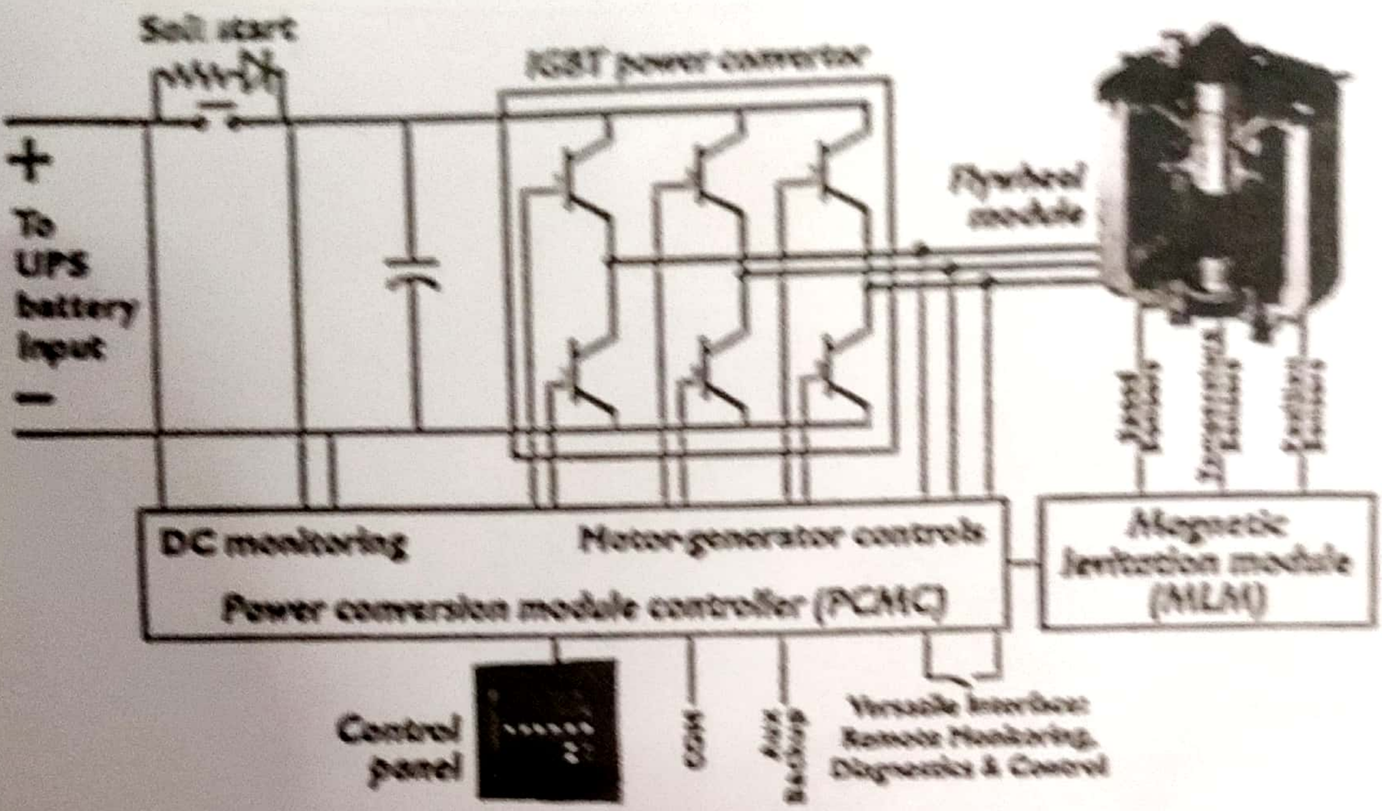
- This can be reduced with multiple small modules

- This can be reduced when used with multiple smaller FWs (Operating as pairs- one in one direction & other in the opposite direction & net will be theoritically zero).

FW ⇒ Sp energy 10 to 150 Whr/Kg
Sp Power 2 to 10 KW/Kg
} Speed around 60000 rpm

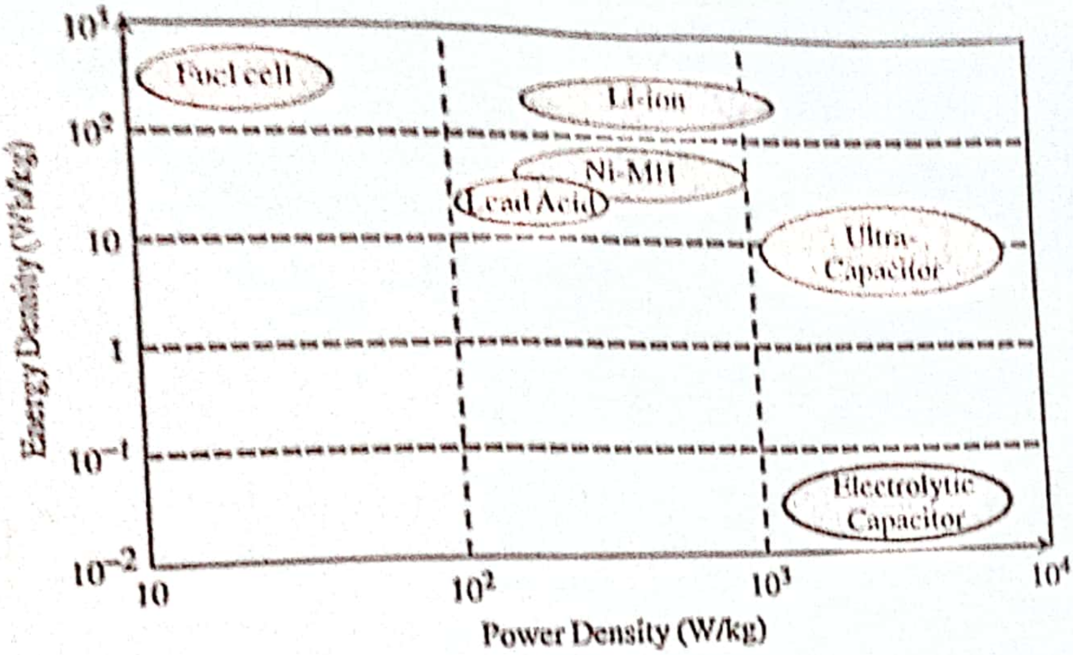


Basic structure of a typical flywheel system (mechanical battery)



Flywheel energy accumulators

⑨



Comparison of power density and energy density for ESS in HEVs

Theoretical Specific Energies of Candidate Batteries for EVs and HEVs[1]

Battery ⊕	⊖	Cell Reaction		Specific Energy (Wh/kg)
		Charge ⇐	Discharge ⇒	
Acidic aqueous solution				
PbO_2	Pb	$PbO_2+2H_2SO_4+Pb$	⇔ $2PbSO_4+2H_2O$	170
Alkaline aqueous solution				
NiOOH	Cd	$2NiOOH+2H_2O+Cd$	⇔ $2Ni(OH)_2+Cd(OH)_2$	217
NiOOH	Fe	$2NiOOH+2H_2O+Fe$	⇔ $2Ni(OH)_2+Fe(OH)_2$	267
NiOOH	Zn	$2NiOOH+2H_2O+Zn$	⇔ $2Ni(OH)_2+Zn(OH)_2$	341
NiOOH	H_2	$2NiOOH+H_2$	⇔ $2Ni(OH)_2$	387
MnO_2	Zn	$2MnO2+H_2O+Zn$	⇔ $2MnOOH+ZnO$	317
O_2	Al	$4Al+6H_2O+3O_2$	⇔ $4Al(OH)_3$	2815
O_2	Fe	$2Fe+2H_2O+O_2$	⇔ $2Fe(OH)_2$	764
O_2	Zn	$2Zn+2H_2O+O_2$	⇔ $2Zn(OH)_2$	888
Flow				
Br_2	Zn	$Zn+Br_2$	⇔ $ZnBr_2$	436
Cl_2	Zn	$Zn+Cl_2$	⇔ $ZnCl_2$	833
$(VO_2)_2SO_4$	VSO_4	$(VO_2)_2SO_4+2HVSO_4$ $+2H_2SO_4$	⇔ $2VOSO_4+V_2(SO_4)_3$ $+2H_2O$	114
Molten salt				
S	Na	$2Na+3S$	⇔ Na_2S_3	760
$NiCl_2$	Na	$2Na+NiCl_2$	⇔ $2NaCl$	790
FeS_2	LIA1	$4LIA1+FeS_2$	⇔ $2Li_2S+4Al+Fe$	650
Organic lithium				
$LiCoO_2$	Li-C	$Li_{(y+x)}C_6+Li_{(1-(y-x))}CoO_2$	⇔ $Li_yC6+Li_{(1-y)}CoO_2$	320[a]

Status of Battery Systems for Automotive Applications

System	Specific Energy (Wh/kg)	Peak Power (W/kg)	Energy Efficiency (%)	Cycle Life	Self-Discharge (% per 48 h)	Cost (US$/kWh)
Acidic aqueous solution						
Lead/acid	35–50	150–400	>80	500–1000	0.6	120–150
Alkaline aqueous solution						
Nickel/cadmium	50–60	80–150	75	800	1	250–350
Nickel/iron	50–60	80–150	75	1500–2000	3	200–400
Nickel/zinc	55–75	170–260	65	300	1.6	100–300
Nickel/metal hydride	70–95	200–300	70	750–1200+	6	200–350
Aluminum/air	200–300	160	<50	?	?	?
Iron/air	80–120	90	60	500+	?	50
Zinc/air	100–220	30–80	60	600+	?	90–120
Flow						
Zinc/bromine	70–85	90–110	65–70	500–2000	?	200–250
Vanadium redox	20–30	110	75–85	—	—	400–450
Molten salt						
Sodium/sulfur	150–240	230	80	800+	0[a]	250–450
Sodium/nickel chloride	90–120	130–160	80	1200+	0[a]	230–345
Lithium/iron sulfide (FeS)	100–130	150–250	80	1000+	?	110
Organic/lithium						
Lithium-ion	80–130	200–300	>95	1000+	0.7	200

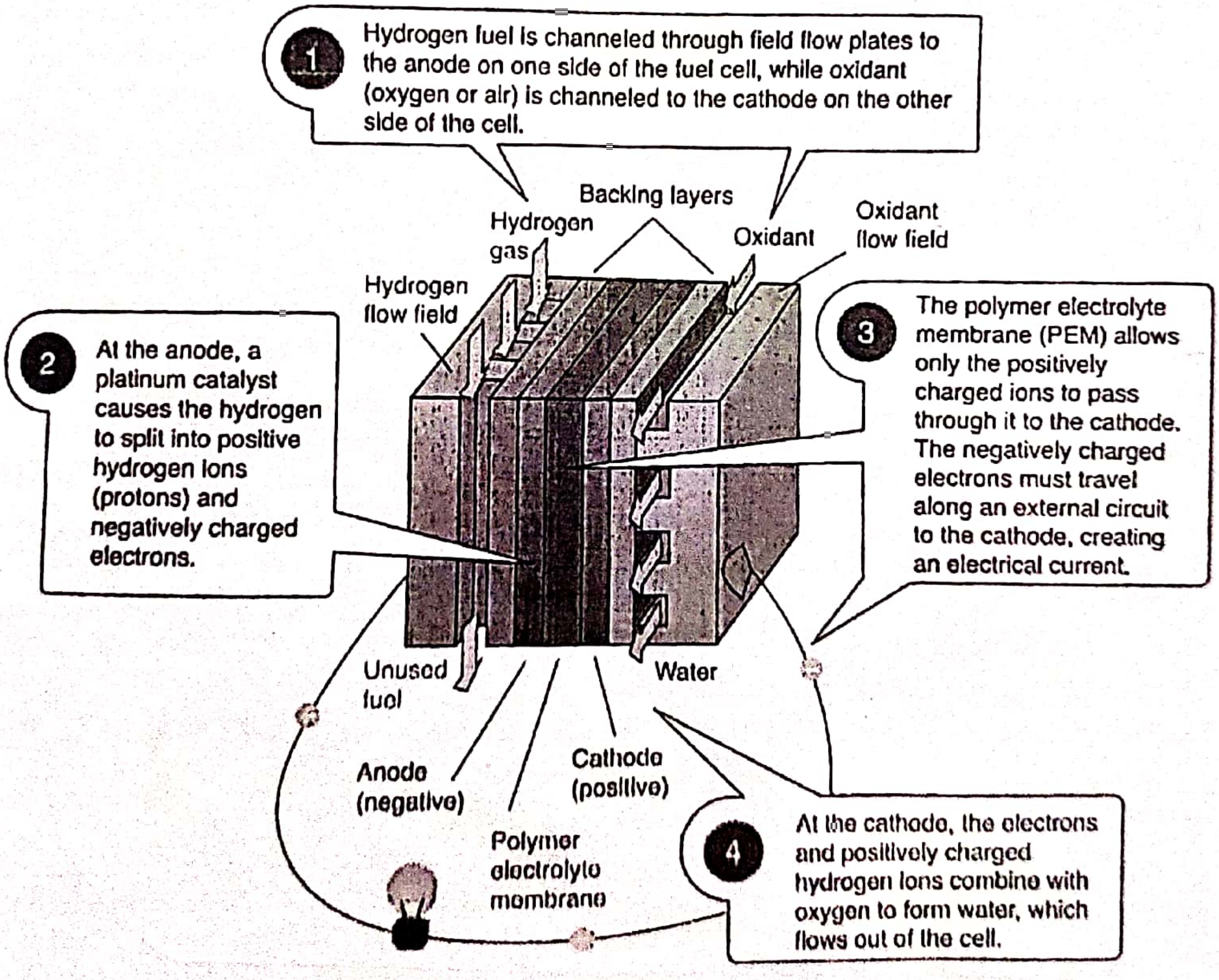
[a] No self-discharge, but some energy loss by cooling.

Fuel Cell

- The energy of oxidation of conventional fuels which is usually manifested as heat can be converted directly into electricity in a fuel cell.
- All oxidation involve a transfer of electrons between fuel & oxidant in the fuel cell converts the energy directly to electricity.
- All battery cell involve an oxide reduction at positive electrode & oxididation at negative electrode during chemical process.
- In Fuel Cell (FC) anode, catthode & electrolyte are required. The electrolyte is fed directly with the fuel.
- It has been found that a fuel of hydrogen when combined with oxygen proves to be the most efficient design.

- Hydrogen is passed over the anode which is coated with a catalyste, the hydrogen diffuses into the electrolyte This causes electrons to be stripped off the hydrogen atoms. Then passes through the external circuit.

Proton exchange membrane fuel cell



① Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell, while oxidant (oxygen or air) is channeled to the cathode on the other side of the cell.

② At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.

③ The polymer electrolyte membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current.

④ At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell.

- Negatively charged Hydrogen anions (OH) are formed at the electrodes over which oxygen is passed such that it also diffuses into the solution. These onions move through the electrolyte to anode. The water thus formed flows out of the cell.
- Working temperature of FC is about 200°c
- High pressure is also used in the order of 30 bar.
- The pressure & storage of Hydrogen are the main problems associated.
- Many combination of fuel & oxidant are possible for FC.

Methonal can be used in FC

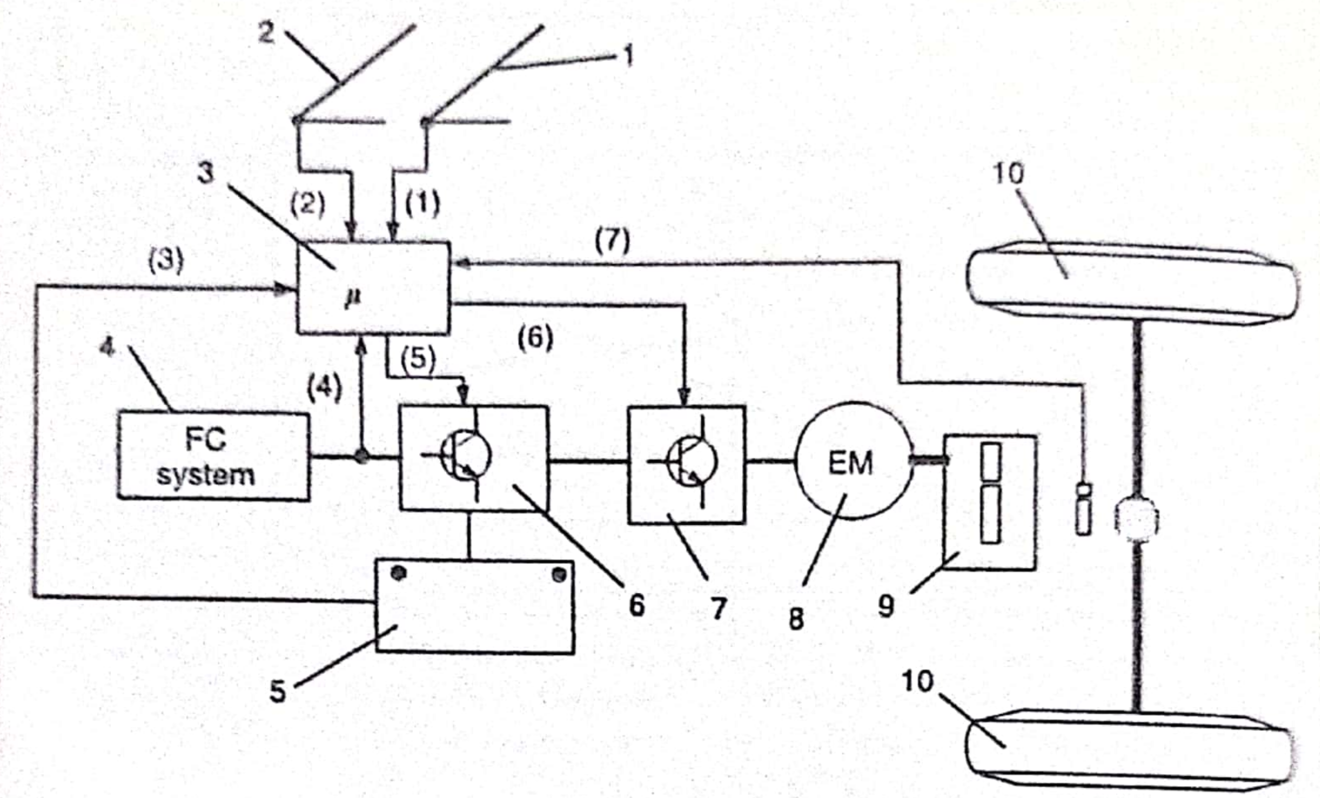
Direct Methonal Fuel Cell

- It is a type of Proton Exchange Membrane Fuel Cell (PEMFC)

Reformed Methonal Fuel Cell

- A reaction is used to release Hydrogen from Methonal & then the FC runs with Hydrogen.

- The membrane acts as electrolyte & the Protons (Positively charged Hydrogen ion) carry electrical charge between the electrodes.
- Here fuel is Methonal not hydrogen.
- Methonal is a Hydro-Carbon (HC) fuel. It Contains Hydrogen & Carbon as well as oxygen.
- When HC burned Hydrogen reacts with oxygen to create water & Carbon reacts with oxygen creats CO_2
- Methonal can be easily fit into the existing fuel infrastructure.
- Methonal is used as a carrier for Hydrogen.
- More efficient to use but Complex.



1: accelerator pedal; 2: brake pedal; 3: vehicle controller; 4: fuel cell system; 5: peaking power sound; 6: electronic interface; 7: motor controller; 8: traction motor; 9: transmission; 10: wheels. (1): traction command signal; (2): braking command signal; (3): energy signal of peaking power sour; (4): fuel cell power signal; (5): electronic interface control signal; (6): motor control signal; (7): speed

Fig. Configuration of a typical Fuel Cell Hybrid Drive Train.

- FC – Hydrogen Energy Storage System includes 3 key Components
  - Electrolysis which Consumes off peak electricity to produce hydrogen
- FC uses that Hydrogen & oxygen from air to generate peak hour electricity.

(10) Ultra Capacitor:

- UC is found to be the prime power Source which is characterized by much higher Sp. power but much lower Sp. energy Compared to Chemical batteries.
- The discharging & Charging profile of Energy storage is highly varying due to the frequent stop/go operation of EVs.
- The average power required from Energy Storage is much lower than the peak Power of relatively short duration especially for acceleration & hill climbing.
- Ratio of peak power to average power Can be over 10:1
- In HEV design peak Power Capacity of Energy Storage Systems (ESS) is more important than its energy Capacity.
- In HEV design battery design should ensure high Sp. energy, high Sp. power better life cycle. But these are not that

much easy. so hybiridigation of Energy Storage (ES) & Power Storage (PS) are required.

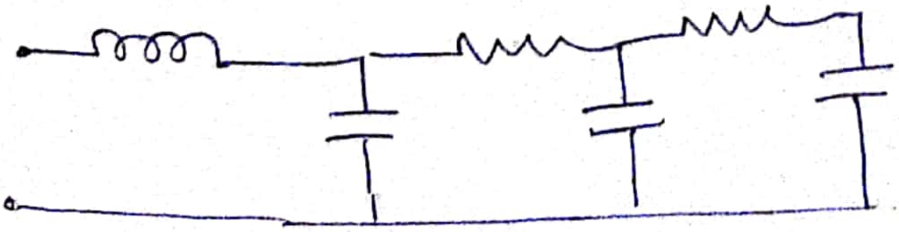
ES: Battery & Fuel Cell have high Sp. Energy.

The **PS** Power Sources Can be recharged from the ES during less demanding driving or regenerative braking.

UC Sp power Can reach upto 3KW/kg but Sp. Energy few Wh/kg

- Due to their low. sp. energy density & dependance of voltage on the SOC it is difficult to use UC alone as ESS for EVs.
- Double Layer Capacitor technology is widely used in UC
- Basic Principle: When 2 Carbon rods are immersed in a thin Sulfuric acid solution separated from each other Charge from 0 to 1.5 V. After 1.2V electrical decomposition of water create bubbles →

- Below decomposition voltage, while the current doesnot flow an "electric double layer" occurs at the boundary of electrode & electrolyte.
- The electrons are charged across the double layer & for a capacitor.
- An electrical double layer works as an insulator only below the decomposition voltage.
- Super Capacitor (SC) get their name from their ability to store high energy. This can be done by increasing the area of the parallel plates in a capacitor.
- Capacitance can be increased or decreased by the seperation betwen the parallel plates $C = \frac{\epsilon A}{d}$
- 3^{rd} order UC model is used for EV



acounting a frequency range t
0.0034 to 1.44
HZ.

Ultra capacitors

- An **Ultra Capacitor**, also known as a **Super Capacitor**, or **electrochemical capacitor,** is a device for storing electrical energy which is growing rapidly in popularity.

- Dr **David Eisenberg** and Prof. **Gadi Rothenberg** of the University of Amsterdam's **Van 't Hoff** Institute for Molecular Sciences have invented a new type of super capacitor material with a host of potential applications in electronics, transportation and energy storage

- **Super Capacitors** are **electric** storage devices which can be recharged very quickly and release a large amount of power. In the **automotive** market they cannot yet compete with Li-ion batteries in terms of energy content, but their capacity is improving every year.

- **Electrical energy** is **stored in Super Capacitors** via two **storage** principles, static double-layer capacitance and electrochemical pseudo capacitance; and the distribution of the two types of capacitance depends on the material and structure of the electrodes.

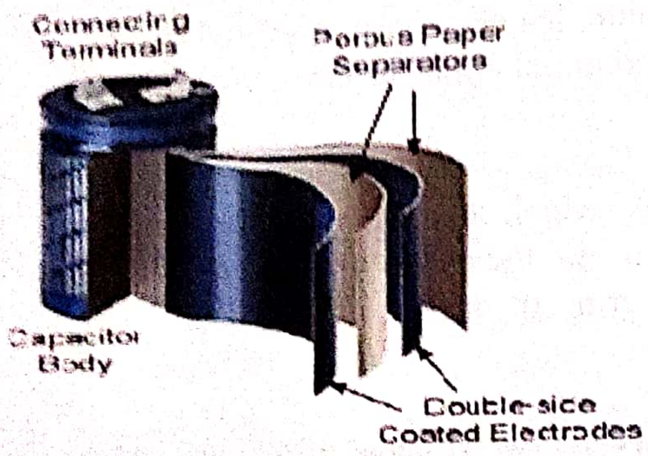
- **Ultra Capacitors** also have two metal plates, but they are coated with a sponge-like, porous material known as activated carbon. And they're immersed in an electrolyte made of positive and negative ions dissolved in a solvent. This then causes each electrode to attract ions of the opposite charge.

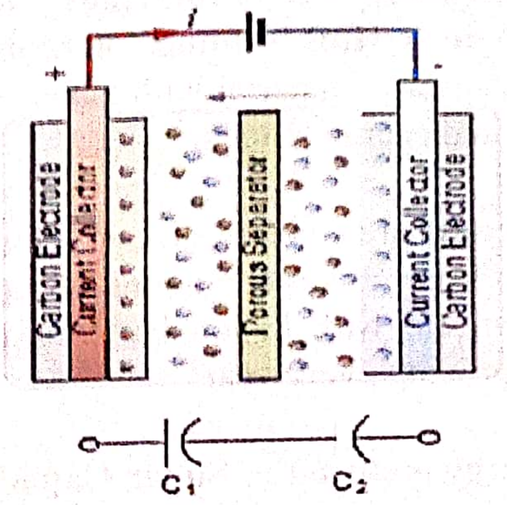
- The small separation between electrodes permitted by this structure lead to much higher energy storage density than a normal capacitor. The double sided coated electrodes are made from graphite carbon in the form of activated conductive carbon, carbon nanotubes or carbon gels.

- A porous paper membrane called a separator keeps the electrodes apart but allows positive ion to pass through while blocking the larger electrons.

Both the paper separator and carbon electrodes are impregnated with the liquid electrolyte with an aluminum foil used in between the two to act as the current collector making electrical connection to the ultra capacitors solder tabs.

The double layer construction of the carbon electrodes and separator may be very thin but their effective surface area into the thousands of meters squared when coiled up together.



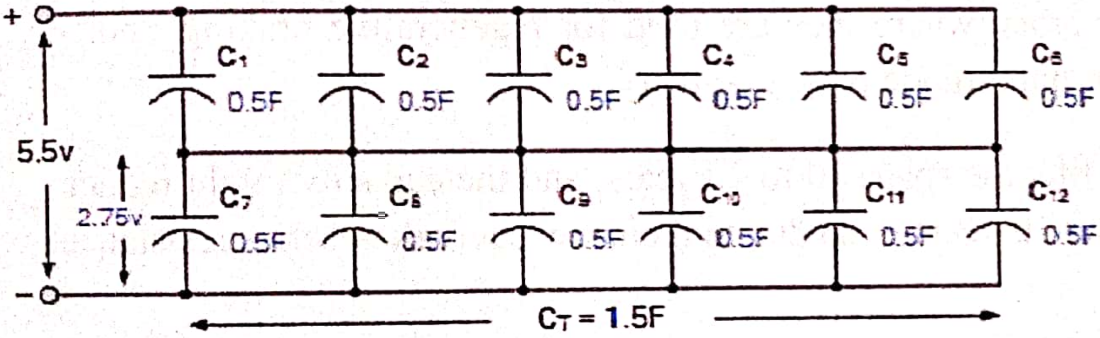


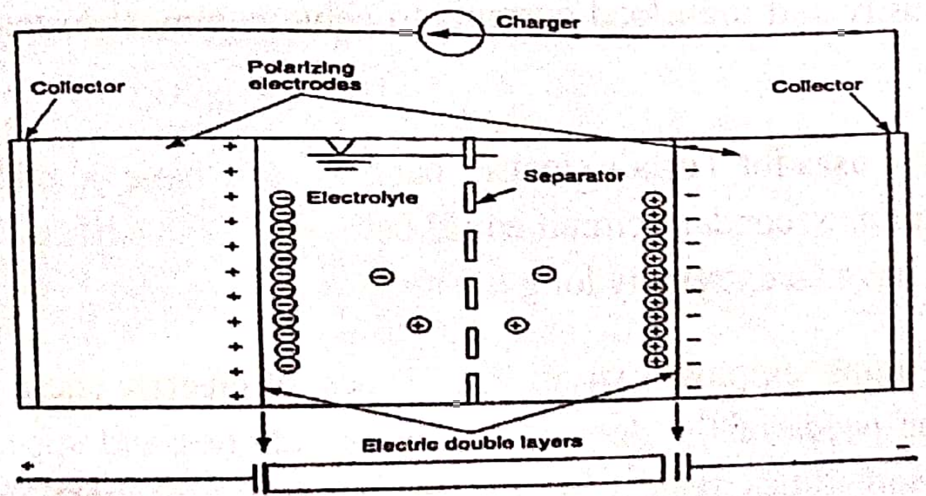
Then in order to increase the capacitance of an ultra-capacitor, it is obvious that to increase the contact surface area, A (in m^2) without increasing the capacitors physical size, or use a special type of electrolyte to increase the available positive ions to increase conductivity.

Then **ultra-capacitors** make excellent energy storage devices because of their high values of capacitance up into the hundreds of farads, due to the very small distance (d) or separation of their plates and the electrodes high surface area (A) for the formation on the surface of a layer of electrolytic ions forming a double layer. This construction effectively creates two capacitors, one at each carbon electrode, giving the ultra capacitor the secondary name of "double layer capacitor" forming two capacitors in series.

However, the problem with this small size is that the voltage across the capacitor can only be very low as the rated voltage of the ultra-capacitor cell is determined mainly by the decomposition voltage of the electrolyte. Then a typical capacitor cell has a working voltage of between 1 to 3 volts, depending on the electrolyte used, which can limit the amount of electrical energy it can store.

- In order to store charge at a reasonable voltage ultra capacitors have to be connected in series. Unlike electrolytic and electrostatic capacitors, ultra-capacitors are characterized by their low terminal voltage. In order to increase their rated terminal voltage to tens of volts, ultra capacitor cells must be connected in series, or in parallel to achieve higher capacitance values. 6x2 UCs placements is shown below





- An ***Ultra Capacitor*** (UC) is an electrochemical device consisting of two porous electrodes, usually made up of activated carbon immersed in an electrolyte solution that stores charge electrostatically. This arrangement effectively creates two capacitors, one at each carbon electrode, connected in series.

Sometimes called an Ultra Capacitor (UC), a Super Capacitor (SC) - like a battery - is a means to store and release electricity. But rather than storing **energy** in the form of chemicals, super capacitors store electricity in a static state, making them better at rapidly charging and discharging **energy**.

Super Capacitor (SC) is often misunderstood; it is not a **battery replacement** to store long-term energy. If, for example, the charge and discharge times are more than 60 seconds, use a **battery**; if shorter, then the **SC** becomes economical.

Super Capacitors are used in applications requiring many rapid charge/discharge cycles, rather than long-term compact energy storage - in automobiles, buses, trains, cranes and elevators, where they are used for regenerative braking, short-term energy storage, or burst-mode power delivery.

A **Super Capacitor's** lifetime spans 10 to 20 years, and the capacity might reduce from 100% to 80% after 10 years or so due to their low equivalent series resistance (ESR).

SCs provide high power density and high load currents to achieve almost instant charge in seconds.

SCs still hold some potential **uses** for **Tesla's** electric cars. If you have a high energy battery onboard, then this secondary circuit **could** be powered by a **SC** that is very efficient. It **will** even have an extremely long life cycle.

All-**electric vehicle** power trains employ two distinct types of **electric** energy storage devices to satisfy the needs of the design. These are batteries and super capacitors, the latter also sometimes being referred to as ultra capacitors or electrochemical **capacitors**.

The energy density of **SCs** pale against lithium ion **batteries**, the technology typically used today in phones and laptops. For that purpose, **SCs can replace batteries** entirely on hybrid buses, while all-electric buses require fewer **batteries**.

PowerStor **SCs** have a longer lifetime than secondary batteries, but their lifetime is not infinite. Over many years, the **SC** will dry **out**, similar to an electrolytic capacitor, causing high ESR and eventually end-of-life.

- Ruthenium dioxide (RuO_2) + Carbon electrodes

Cost high
limited availability

both have high
surface area

- Hybrid Buses uses 30 UC to store 1600 KJ of elec energy (20 Farads at 400 V) Mass 950 kgs.
- UC can be charged in a very short space of time compared with batteries.

In UC

Stored $Q = CV$

Energy $(E) = \frac{1}{2} CV^2$

Note Capa rated voltage with an aqueous electrolyte has been upto 0.9 V per cell & 2.3 to 3.3V for each cell with nonaqueous

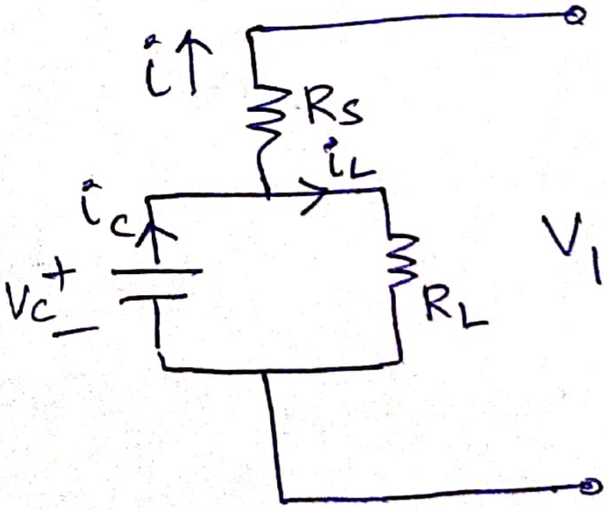
using double layer (very thin) in the place of plastic or aluminium oxide films

Capa/area is quite large

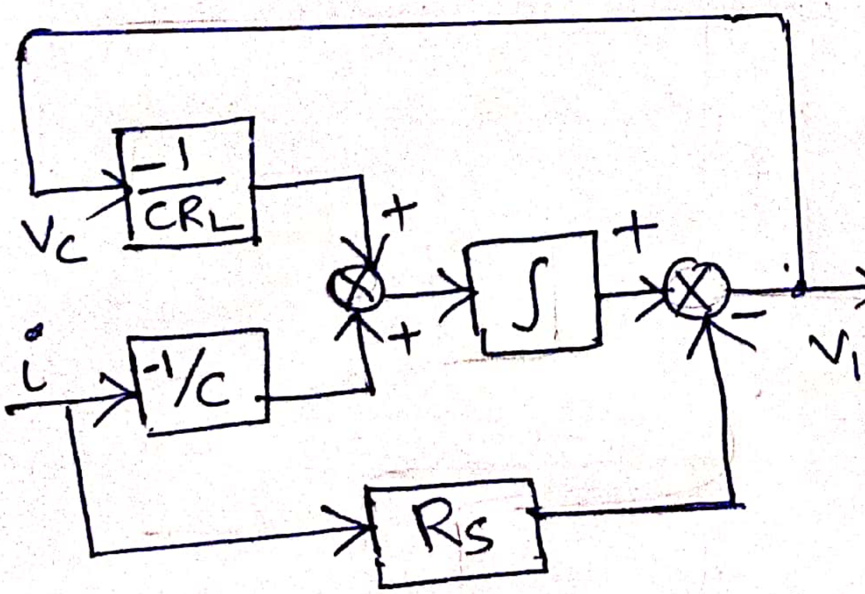
2.5 to 5 $\mu F/cm^2$

⑪ Aluminium foil when used in UC may not increase the energy density so to increase the Capa, electrodes made from specific materials like activated Carbon (have high surface area of 1000 to 3000 m^2/g)

- The Sp. energy of UC at present is about 2 Whr/kg only which is similar to Lead-Acid battery.
- The performance of an UC



Equivalent circuit of UC



Block diagram of UC

During discharging mode

$$V_1 = V_c - iR_s$$

Electric potential of a Capa $= \frac{dV_c}{dt} = \frac{-(i+i_L)}{C}$

where $C \rightarrow$ Capa of UC

Leakage current $i_L = \frac{V_c}{R_L}$

$$\frac{dV_c}{dt} = \frac{V_c}{CR_L} - \frac{i}{C}$$

From block diagram

$$V_c = \left[V_{co} \int_0^t \frac{i}{C} e^{t/CR_L} \cdot dt\right] e^{t/CR_L}$$

initial value

$i \rightarrow$ is the discharge current

Operating efficiency during discharging

$$\eta_{dis} = \frac{V_1 I_1}{V_c I_c} = \frac{(V_c - I_1 R_s) I_1}{V_c (I_1 + I_L)}$$

as I_L is small $\Longrightarrow$ $= \frac{V_c - I_1 R_s}{V_c} = \frac{V_1}{V_c}$

Operating efficiency during Charging

$$\eta_{charging} = \frac{V_c I_e}{V_1 I_1} = \frac{V_c(I - I_L)}{(V_c + I_1 R_s) I_1}$$

$$= \frac{V_c I_1}{V_c + R_s I_1} = \frac{V_c}{V_1}$$

The operation of UC should be maintained at its high voltage region (more than 60% of rated voltage)

$$\text{Energy stored in UC} = E_c = \int_0^t V_c I_c \, dt$$

$$= \int_0^v C V_c \, dV_c = \frac{1}{2} C V_c^2$$

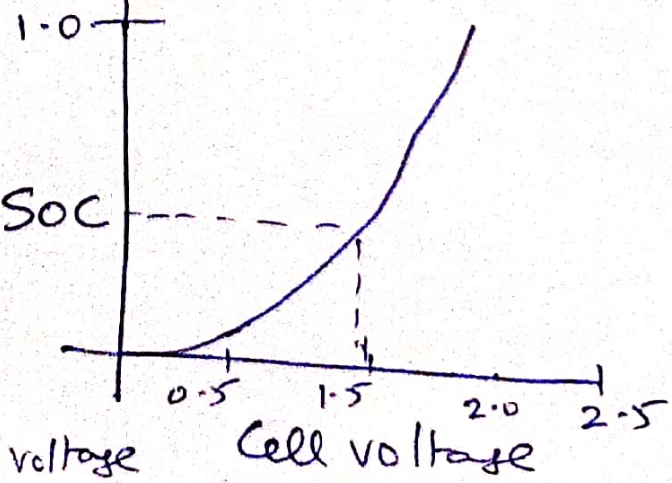
↑ Cell voltage.

At rated voltage the energy stored in UC reaches its maxima

UC are designed to deliver energy when the available voltage is more than the bottom voltage V_b

Useful (or) available energy in UC

$$= \frac{1}{2} C\Big(\underset{\substack{\uparrow \\ \text{rated voltage}}}{V_{CR}^2} - V_{Cb}^2\Big) \rightarrow \text{bottom voltage}$$



$$SOC = \frac{0.5 C V_{Cb}^{2}}{0.5 C V_{CR}^{2}} = \frac{V_{Cb}^{2}}{V_{CR}^{2}}$$

When Cell Voltage drops from rated voltage to 60%. i.e $V_c = 1.5$; $SOC = 0.36$ (from graph)

available $= 1 - 0.36 = \underline{\underline{64\%}}$

UC's SOC is easy to estimate as it requires only the voltage measurement.

UC allow rapid charging & discharging

UC have long life cycle (Million cycles).

⑫ Hybridization of different Energy Storage Devices.

- The hybridization of Energy Storage is to combine 2 or more energy storing devices so that the advantages of each one can be brought out & the disadvantages can be compensated by the others.

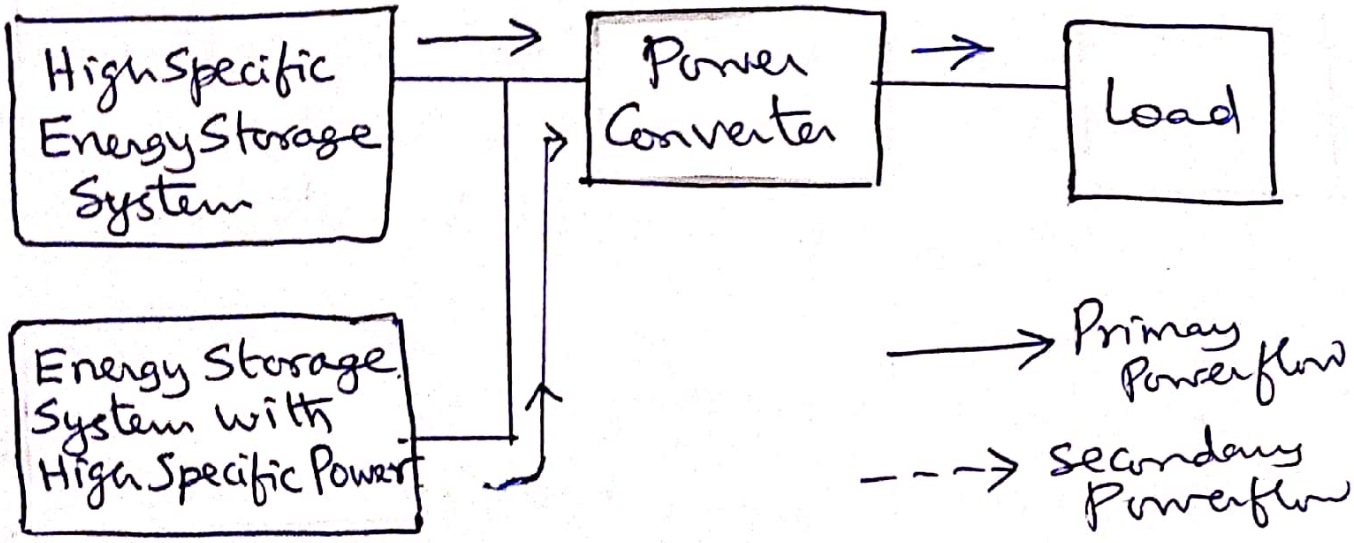
Eg

- Hybridization of a chemical battery with the an Ultra Capacitor can overcome the problems like low specific power of electro chemical batteries & low specific energy of ultra capacitors ensuring high specific energy & high specific Power.
- Hybridization between high specific energy storing devices & high specific Power energy storing devices be made efficient based on the necessary usage of them for different operating Conditions

i) High Power Demand Operating Condition

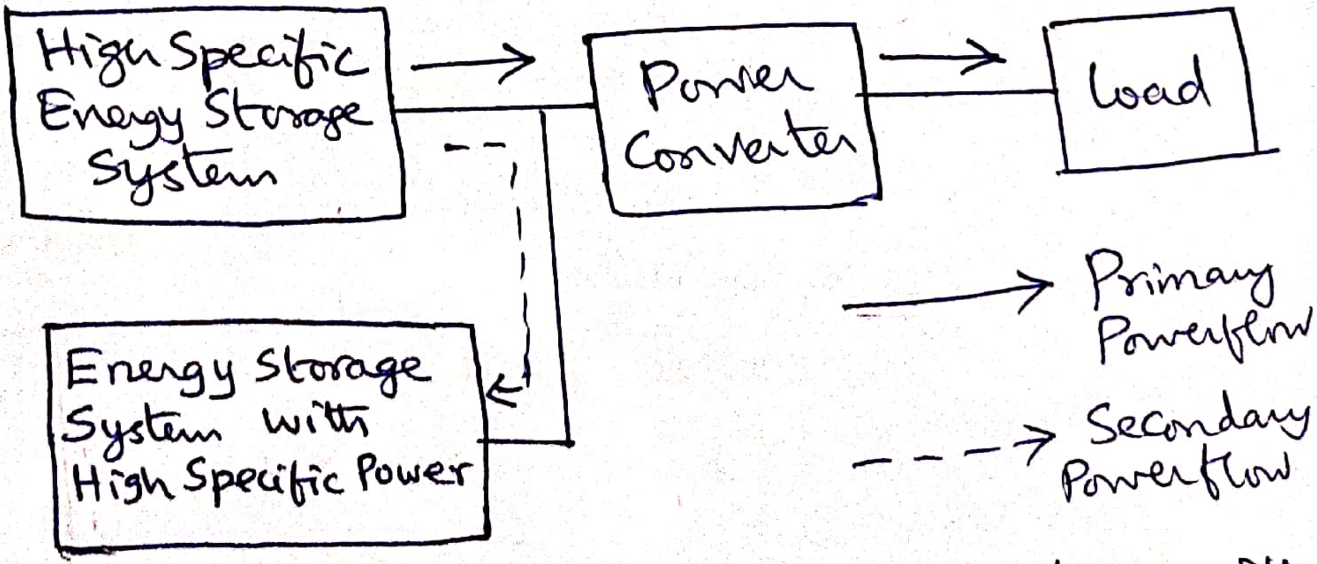
(Acceleration, hill climbing)

- Both basic Energy storing devices deliver their power to the load.



ii) Low Power Demand Operating Condition

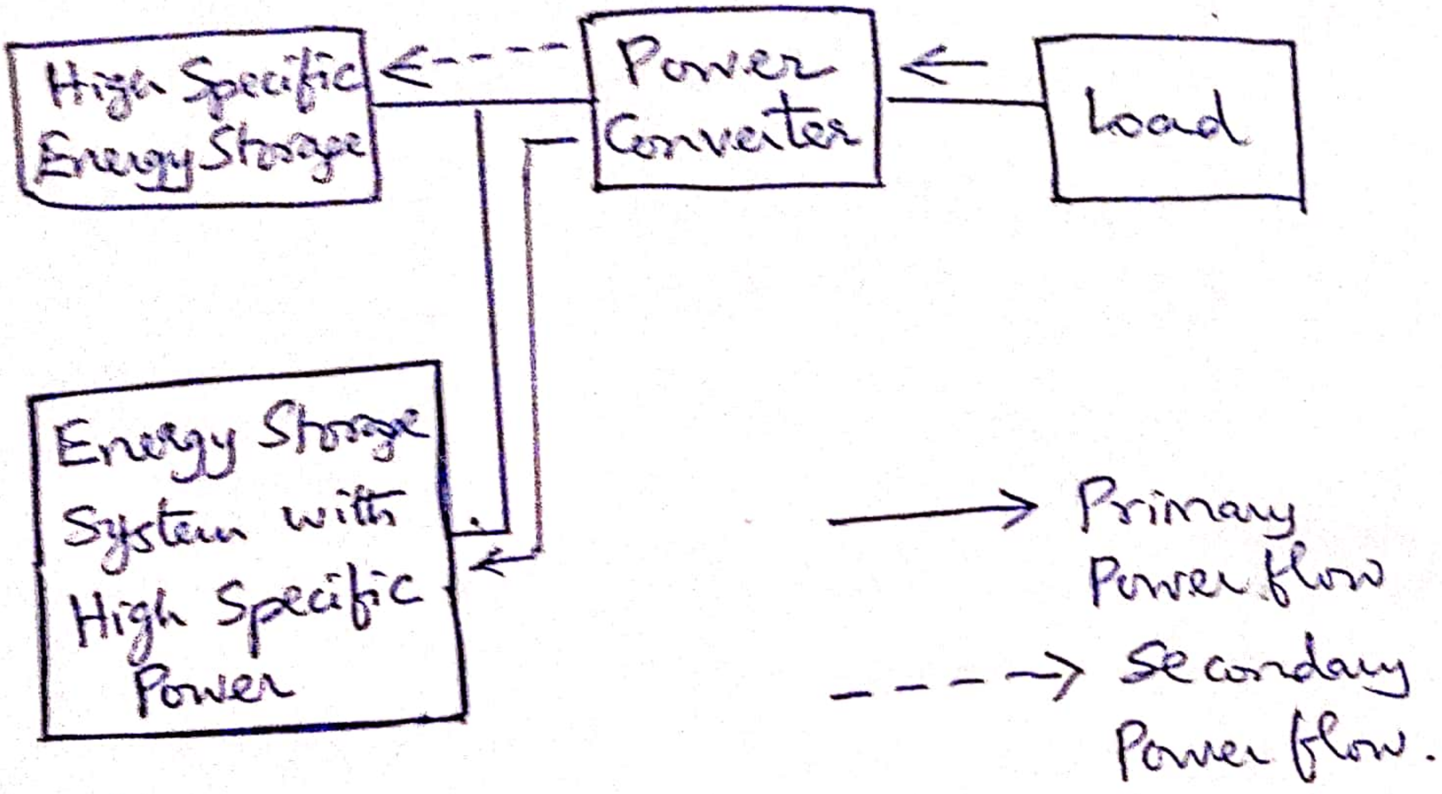
(Constant Speed Cruising)



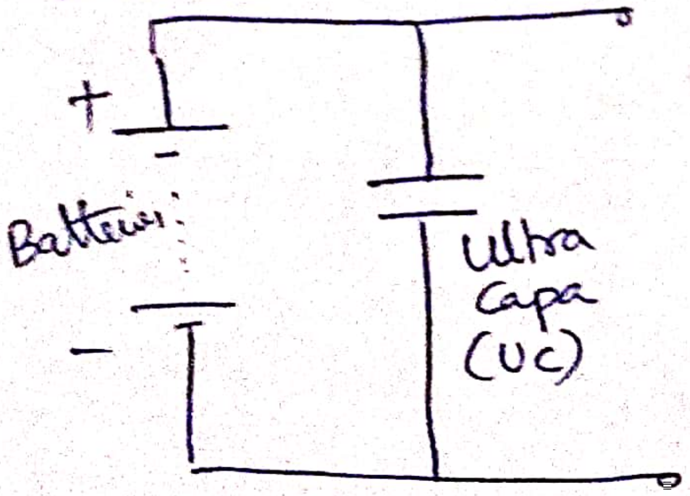
- Here High Specific Energy Storage System will deliver its power to the load & Charge the Energy Storage System with high Specific power to recover its Charge lost during the high power demand operation.

(iii) Regenerative Braking Operation :

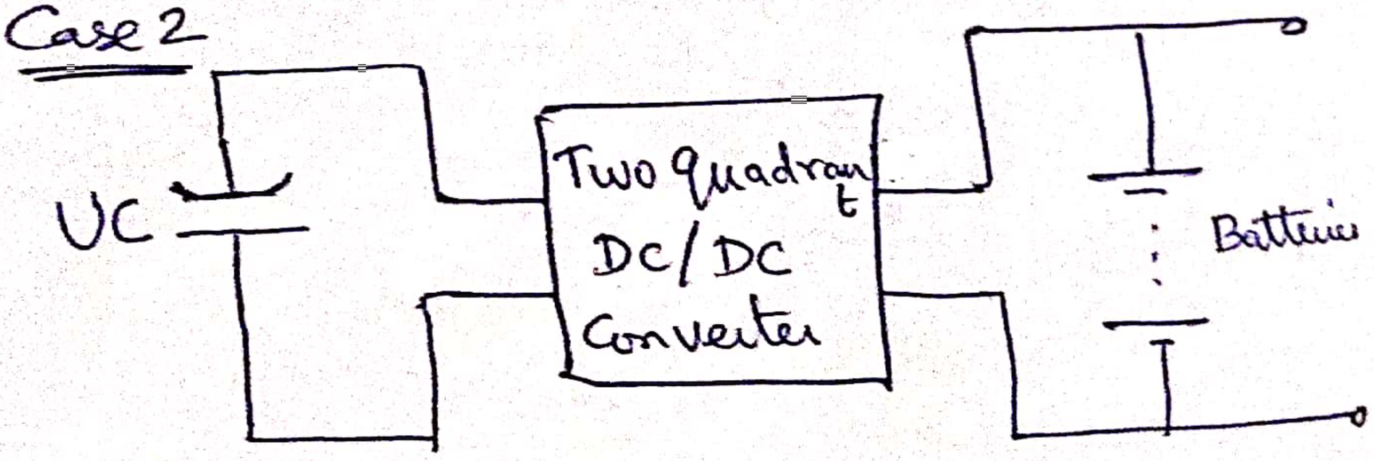
- In the regenerative braking operation, the peak power will be absorbed by Energy Storing System with high Specific Power & only limitted part is absorbed by the high specific Energy Storage System
- Based on the technologies available several viable hybridization schemes for EVs & HEVs typically battery hybrids & battery - UltraCapacitor hybrids
- During hybridization, the simplest way is to Connect the UCs to batteries directly & in Parallel as shown below



Case 1



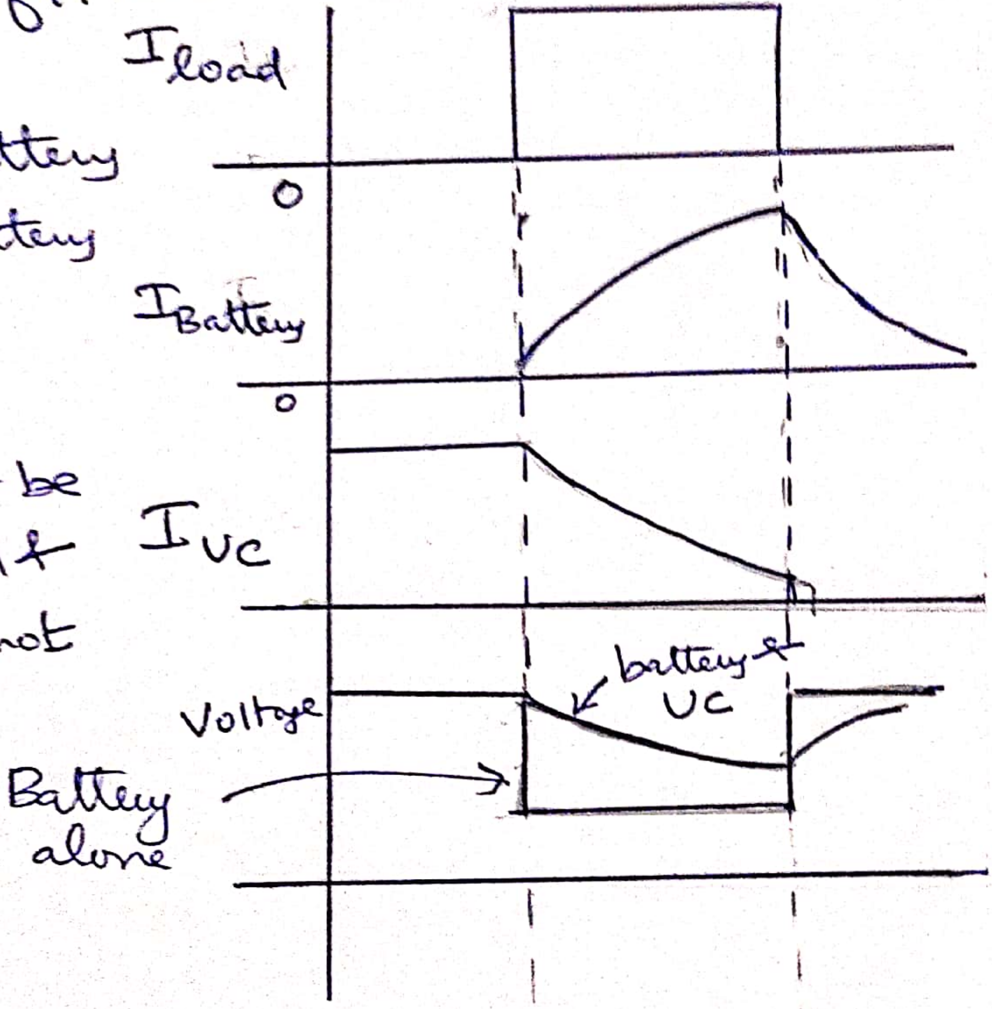
Case 2



- This Configuration Case 2

In Case 1 :-

In this Configuration, the UC simply acts as a current filter which can significantly level the peak current of the battery & reduce the battery voltage drop.



Disadv

- Power flow cannot be actively controlled &
- UC energy cannot be fully used.

Case 2

A two quadrant DC-DC converter is placed between the batteries & UCs. This design allows battery & UC can have different voltages.

- The power flow between them can be actively controlled & the UC energy can be fully used.

⑬ Sizing of Components

- Sizing of Components of electric & mech system depends on the drive train structure adopted in the HEVs.

- In Series HEV (SHEV) the electrical system design is similar to that of EVs. The ICE is specified for keeping the battery charged.

- The sizing of components in Parallel HEV (PHEV) is more complex.
  - If the vehicle is designed to have the biasing with ICE for which the battery can be downsized & reconfigured for a maximum Specific Power instead of maximum Specific energy.
  - The battery & Motor serve to supply peak power demands. For acceleration & over taking without being discharged the motor or ICE (if available) take care.

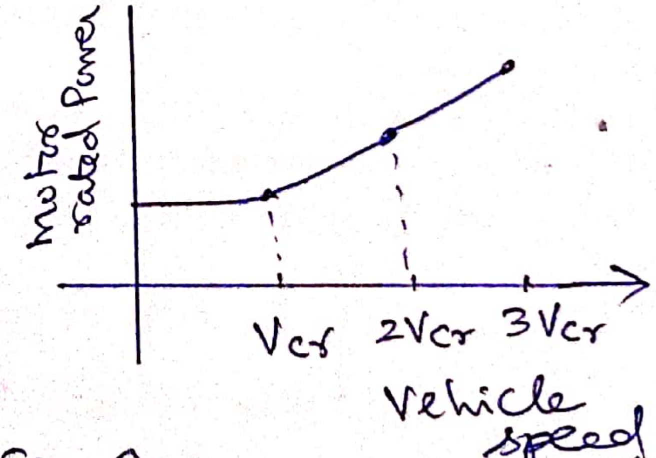
- The battery also acts as a reservior for regenerative braking energy.
- Ultra Capacitors (UC) can be used instead of battery to meet the Peak power demand.

- If the vehicle is to be more battery biased then
  - the batteries in the system will reach about 80% DOD at the end of the longest trip.
- once the power requirements of the elec & mech systems are appropriationed for Parallel HEV, then the elec systems are designed similar to that of the elec system designed for EVs.

- The Mechanical Sub system's Components are sized based on
  - Initial acceleration
  - Rated cruising velocity
  - Maximum velocity.
  - maximum gradability

- The gear ratio between the ICE & the wheel shaft be obtained matching the maximum speed of the ICE to the maximum speed of the drive shaft that can be made simplified when uses with single gear transmission system.

- Initial Acceleration :
  - Motor used with its higher peak power capabilities & adds with mech power from ICE for acceleration which can reduce the motor power requirements.



- V_{cr} ⇒ critical velocity
- The power required from the motor depends on the velocity at which torque blend from the second propolusion unit starts.
- From fig there will be a little power contribution

- Fig Elec power required as a function of vehicle speed at which ICE added.

from ICE until a mini critical velocity (V_{cr}) of the vehicle is reached due to its (poor) low speed – torque capability.

- The power requirement from the motor increases nonlinearly with the speed if the ICE torque blending is delayed beyond V_{cr}.
- The power requirement from the ICE is obtained from the rated vehicle velocity condition that would typically enough to provide for the acceleration in combined with motor.

- **Rated cruising velocity:**
  - In HEV, the motor primarily serves to meet the acceleration requirement while ICE delivers power for cruising at rated velocity assuming that the battery energy is not sufficient to provide the required power throughout the desired range.

∴ ICE size is determined by the vehicle cruising power requirement at its rated velocity independent of the motor power capacity.

- In HEV, the ICE size to be determined first & its size can be used to reduce the power requirement of the motor for acceleration.

- The correct ICE size is determined from the intersection of the worst-case road load characteristic with the ICE force-velocity profile at rated velocity, plus allowing a nominal 10% margin for battery pack recharging.

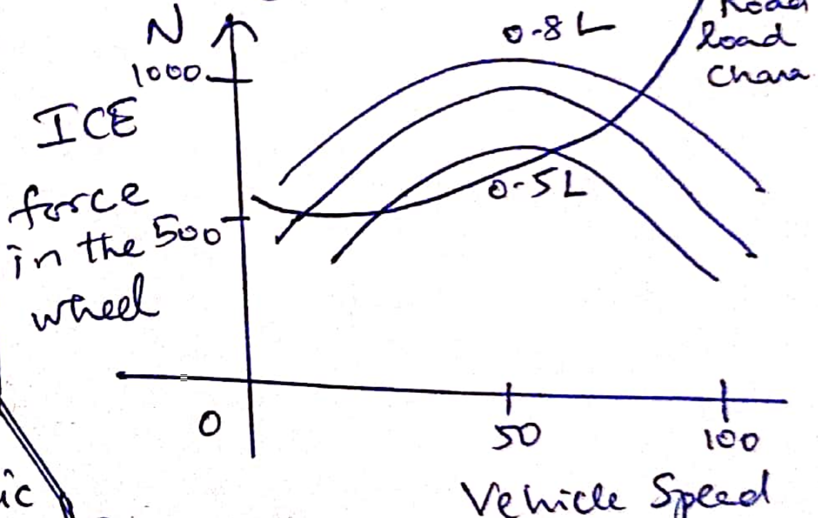


Fig. Typical ICE force-veloci characteristics & road load characteritics.

• Maximum Velocity

The power requirement from the propulsion system at maximum velocity is supplied by the combination of ICE & motor.

$$F_T = F_g + F_t = F_g + f_r + F_w$$

grading resistance

Tractive effort of vehicle & rolling resistance.

vehicle front area

$$= M_v g f_r + \frac{1}{2}\rho_0 C_D A_F V_m^2 + M_v g\, i$$

rolling resi coeff

air density.

aerodyn drag coeff

Total mass of vehicle.

Component of wind speed on vehicle moving direction

+ for opposite to vehicle direct

− for same direction

$$= \underbrace{M_v g \sin\alpha}_{F_g} + \underbrace{M_v g f_r \cos\alpha}_{f_r} + \underbrace{\frac{1}{2}\rho_0 C_D A_F V^2}_{F_w}.$$

where α → road angle

Power requirement at F_T with Vehicle maximum velocity

$$= P_{T\max} = F_T \cdot V_m = V_m(F_g + F_r + F_w)$$

$$P_T = V_m M_v g f_r + \frac{1}{2} \rho_0 C_D A_F V_m^3 + V_m M_v g i$$

$$P_T \propto \underset{\text{aerodyn drag force.}}{V_m^3}$$

Vehicle designed with fast acceleration charact-eristics $\underset{\xrightarrow{\text{Motor power rating}}}{P_m}$ likely to be $> P_{T\max}$

If $P_{T\max} > P_m$ is derived earlier to meet the initial acceleration required then $P_{T\max}$ denotes for Motor power rating.

So to meet very high maximum vehicle velocity requirements then the natural mode region of motor can be used to minimize the motor size.

- **Maximum Gradability:**

$$\text{Maximum \% grade} = \frac{F_T \times 100}{\sqrt{(M g v)^2 - F_T^2}}$$

- If the maximum elec motor power derived for acceleration or maximum vehicle velocity is not enough to meet the maximum gradability requirement of the Vehicle, then either the motor power rating or gear ratio has to be increased. When increasing the gear ratio care must be taken not to violate the vehicle velocity requirement. The gear ratio & the motor power to be selected in a coordinated manner to maintain the reasonable size for both Motor & gear.

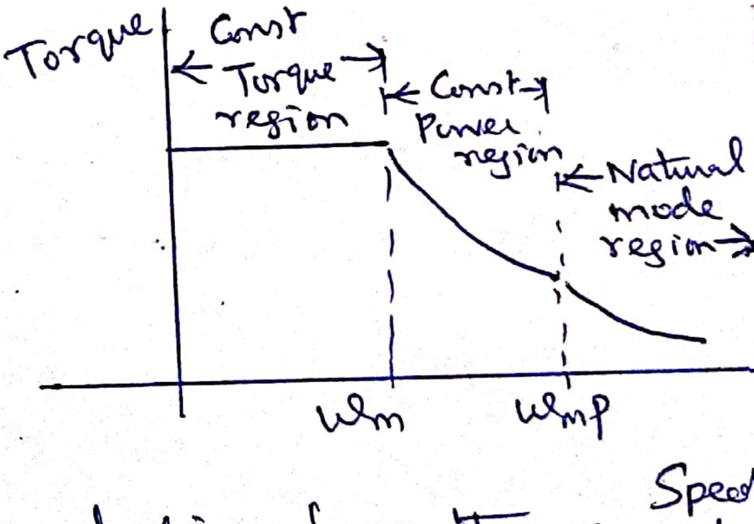
- ICE sizing primarily adopts rated Cruising velocity
- Motor sizing primarily adopts the initial acceleration requirements.

⑭ Electric Motor Sizing

- Electric motors have three major segments in its Torque-Speed Characteristics.
  - Constant Torque region
  - Constant Power region
  - & Natural mode region. (high Speed region)

Constant Torque Region:

- The motor delivers rated torque upto a base speed (or) rated Speed (ω_m) of the motor when it reaches its rated power Condition.



- Motor rated speed is defined as the speed at which the motor Can deliver rated torque at rated power.

Constant Power Region:

- The motor operates in Constant Power region beyond rated speed (ω_m) results falling of torque at a rate that is inversely Proportional to the Speed.

- Motor can be made to operate at speeds higher than rated using field weakening in Constant power region.

Natural mode (or) high Speed region:

- In this, for high Speed operation results in steep fall of Torque may be inversely Proportional to the square of the speed.
- This region is important for certain Motor that can be used to reduce the power rating of the Motor.
- Salient feature of wide operating speed range characteristics of electric Motor makes it possible to eliminate multiple gear ratios & the Clutch in EV & other applications.

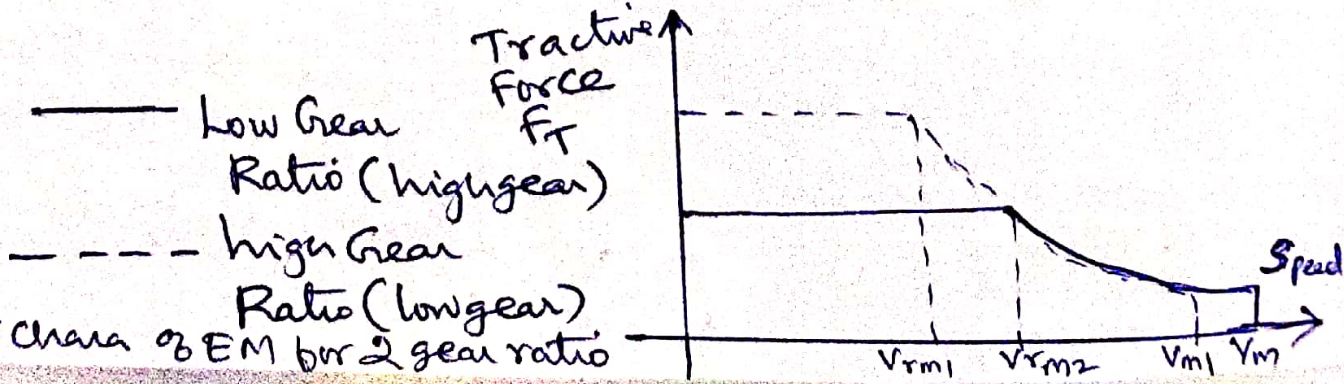


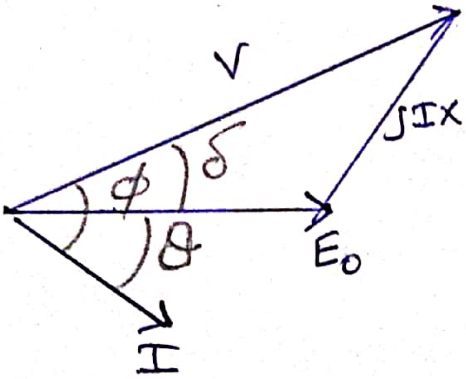
Fig T-N Chara of EM for 2 gear ratio

- Size of an Electric Motor depends on the maximum torque required from the machine.
  (Higher the maximum torque required the larger will be the size of motor)
- In order to minimize the size & weight Elec Motor are designed for high speed operation for a given power rating.
- Gears are used to match the high speed Elec motor with the lower speed of the wheels

  Eg Elec Motor speed 15000 rev/m whereas typical wheel speed 1000 rev/m for light weight passanger vehicle.
- The Transmission (Trm) gears achieves this speed reduction in the range of → 10 to 15 : 1 ; typically 2 stages of 3 to 4 : 1 speed reduction gear sizing depends upon the speed

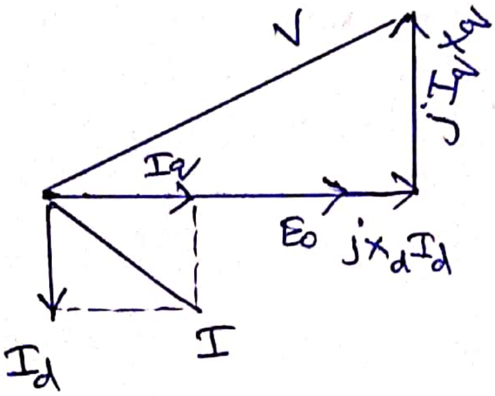
performance (low speed, high speed) of EV is more important.

Design & Sizing of Traction motors

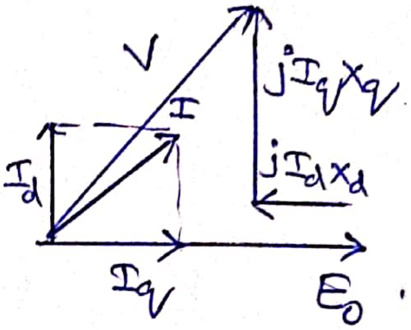


Permanent Magnet (PM) Syn. motor [PSM or SPM]

Surface Mounted PM-motor.



Interior-PM-motor (IPM-motor)



flux weakening of IPM motor.

$V = E_0 + I_R + jIX.$

$V = E_0 + IR + jI_dX_d + jI_qX_q$

E_0 → back emf

Let $\widehat{V \ I} \Rightarrow \phi = \delta + \theta$

Real Power $P_1 = mVI\cos\phi = mIE_0\cos\delta$

$= mV(I\cos\delta\cos\theta - I\sin\delta\sin\theta)$

m → no of phases

θ → angle between current & back emf

δ → angle between voltage & back emf

$I_qX_q = V\sin\theta$

$I_dX_d = V\cos\theta - E_0$

$$\therefore P = \underbrace{\frac{m E_0 V}{X_d} \sin\theta}_{\text{I term}} + \underbrace{\frac{m V^2}{2}\left(\frac{1}{X_q} - \frac{1}{X_d}\right)\sin 2\theta}_{\text{II term}}$$

For SPM $\Rightarrow X_d = X_q$ so IInd term zero.

For IPM $\Rightarrow$ d axis has magnet in its path so larger reluctance

$\boxed{X_q > X_d}$ q axis has soft iron path so less reluctance

$$T = \frac{m I E_0 \cos\delta}{\omega / p} = \frac{m I K \omega \phi}{\omega / p}\cos\delta$$

$$= m P K I \phi \cos\delta$$

$$T_{max} = m P K I \phi = \text{Constant}.$$

The inner power angle $\widehat{E_0 I} = 0$ for a stator current the torque of the motor reaches its maximum.

$$V^2 = E_0^2 + (I_q X_q)^2 = (K\omega\phi)^2 + (I\omega L_q)^2$$

$$\frac{V}{\omega} = \sqrt{(K\phi)^2 + (I L_q)^2} = \text{Constant}$$

$V \propto \omega$ (free) & maintain maximum Torque output at the same time.

This is called <u>Constant Torque Operation</u>

The total current from the inverter is kept the same with the decrease of q axis current from its rated value.

From eqn. $P = \frac{mE_0V}{X_d}\sin\theta + \frac{mV^2}{2}\left[\frac{1}{X_q} - \frac{1}{X_d}\right]\sin 2\theta$

both X_d & E_0 are proportional to freq (ω).

Theoritically Torque is inversily proportional to the freq in this operation. So the **Power is constant** & so this referred as **Constant Power operating region.**

- When stator voltage (V) reaches its max

$$V^2 = (E_0 - I_dX_d)^2 + (I_qX_q)^2 = (K\omega\phi - I_d\omega L_d)^2 + (I_q\omega L_q)^2$$

$$\frac{V}{\omega} = \sqrt{(K\phi - I_dL_d)^2 + (I_qL_q)^2}$$

This equation is also called as the **flux weakening mode** of operation because the d axis current generate a magnetic flux opposite to that of PM field.

$P = m E_0 I \cos\delta$ $\qquad$ $E = 4.44\, k_w f W \phi$

Current density $= I = \frac{\pi D A}{2 m W}$.

$$\phi = \frac{\pi D l}{2P} B\alpha$$

$$P_{max} = m I E_0 = m \frac{\pi D A}{2 m W} 4.44 k_w f W \phi$$

$$= m \frac{\pi D A}{m W} 2.22 K_w \frac{PN}{60} W \frac{\pi D l \; B\alpha}{2P}$$

$$P \propto D^2 A l N$$

(or)

$$D^2 l = K \frac{P}{A l N}$$

$$P = \frac{2\pi N T}{60}$$

$$D^2 l \propto P$$

$$\frac{1}{\propto} N$$

$$\underline{\underline{P \propto NT}}.$$

Elec motor size is $\propto$ T rating

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①

Unit V Energy Management Strategies

Introduction to energy management strategies used in Hybrid & Electric vehicles - Classification of different energy management Strategies - Comparison of different EMS - implementation issues of EMS. Case studies: Design of Hybrid Electric Vehicles (HEV) - Design of a Battery Electric Vehicle (BEV).

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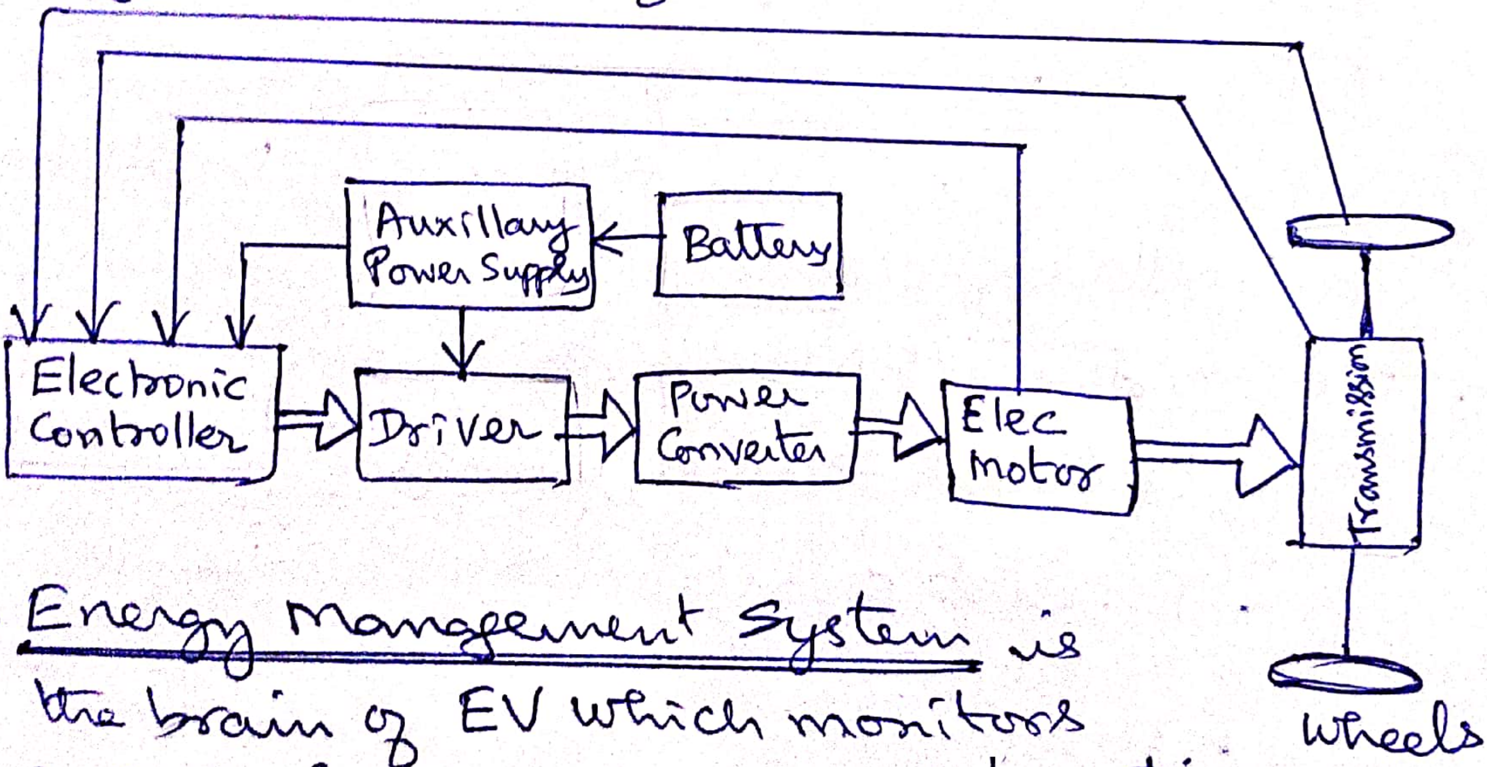
Major Components of EV



- Energy Management System is the brain of EV which monitors & Controls of all required functions.
- This optimizes the charging & discharging of battery for performance improvement & to maximize the operating range.

Energy Management Strategies

- Energy Management Strategy (EMS) is basically a control algorithm which determines how the power is produced in a power train & distributed as a function of the vehicle parameters
- Electrical loads like cranking system communication equipment, air conditioning electronic loads etc & control systems like drive train control, chassis control must be managed effectively to obtain a better efficiency.
- The need for EMS is to
  - optimize energy flow for better efficiency
  - Predict available energy & driving range
  - Propose a suitable algorithm for battery charging.
  - Suggest more efficient driving behavior.

- efficiently utilized the regenerative (braking) energy to charge the batteries / Energy Storing Systems
- report any malfunctions & to Correct them.

- More over EMS is adopted to
  - **Optimize the operating points of ICE** based on Torque-Speed region & to Consider the fuel economy & emission.
  - **Minimize ICE dynamics.** The operating speed is regulated in such a way that any fast fluctuations are avoided, hence ICE dynamics are minimised.
  - **Minimize ICE idle time:**
    - This is to improve the fuel economy & emissions.
  - **optimize ICE ON-OFF times:**
    - This is optimized based on the Driver's habbit, road & weather Condition & traffic situation utilizing

the dual power sources of HEV.

- **Maximize the capturing of regenerative energy:**
  - State of Charge (SOC), Driver's habbit, road & weather Conditions & traffic Conditions.
- **optimize the battery SOC:**
  - obtain a Compromize between battery's life & fuel economy of HEV
- optimize the operating region of the electric motors.
- **Ensure the zero emission policy.**
  - Certain areas like tunnels, workshops in which Elec motor alone is made to operate in HEVs
- Increase the EV range by 10 to 15% & to increase the battery life by 25-30%.

- adjust the lighting brightness with respect to the external environment
- modulate temperature control in response to external climate.
- Energy Management System when coupled with navigation system can able to plan for energy efficient routes locating the charging facilities & to predict the range covered by the vehicle accounting traffic conditions.

Energy management have two tasks in controlling HEV.

Low level (or) Component level Control task

(Here each power train components are controlled using classical feedback control method)

Higer level (or) Supervisory Contro Le

(optimizing energy flow on-board of vehicle while maintaining the battery SOC within a certain range of operation)

EMSystem receives info from vehicle ($\omega_{eng}, \omega_{gh}, \omega_{motor}$) & driver ($V_{veh}, a_{veh}, \delta$) to output & optimizes the Controller in low level Control layer.

- Selects the best modes of operation of HEV

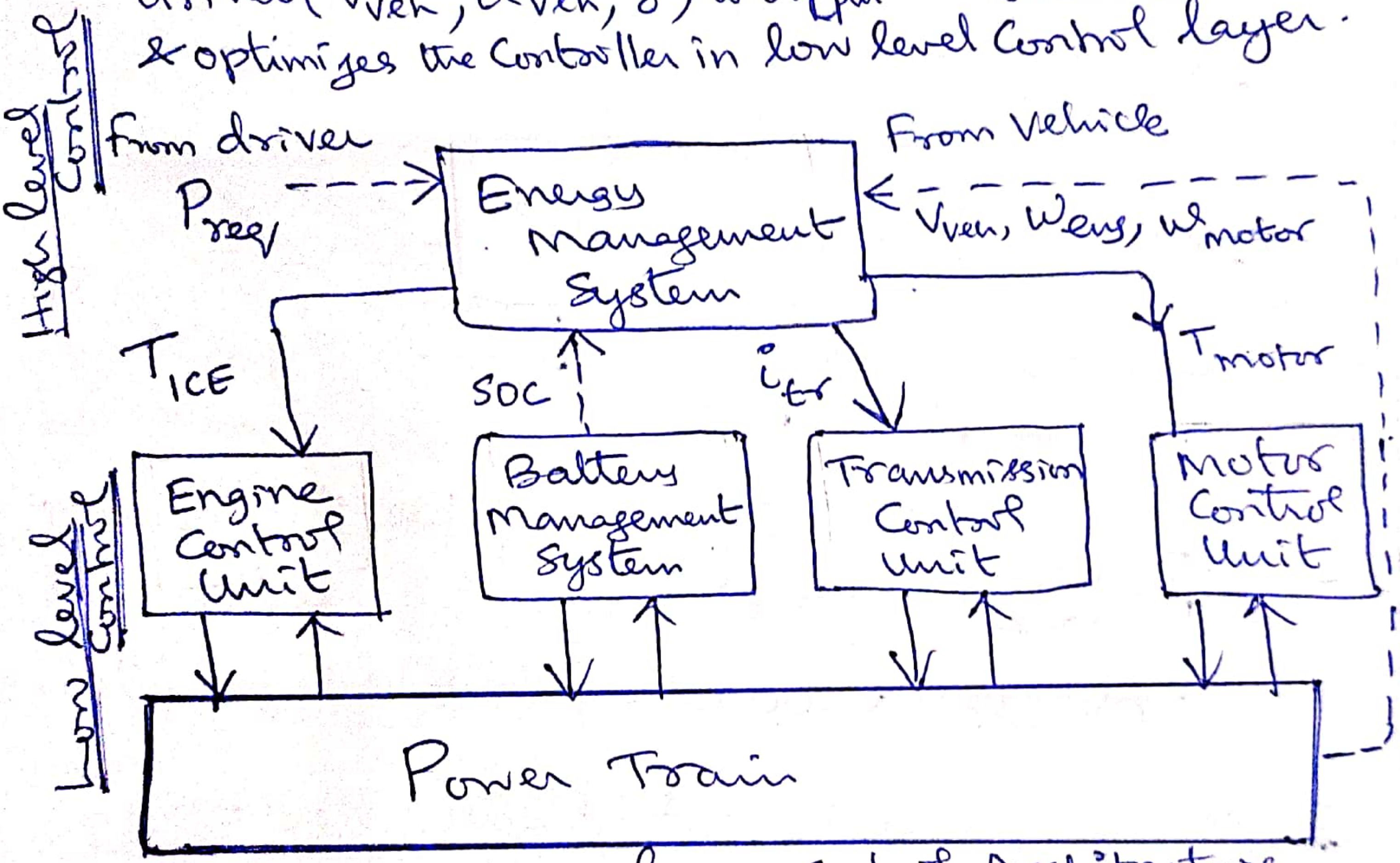


Fig: Two layer Control Architecture in HEV.

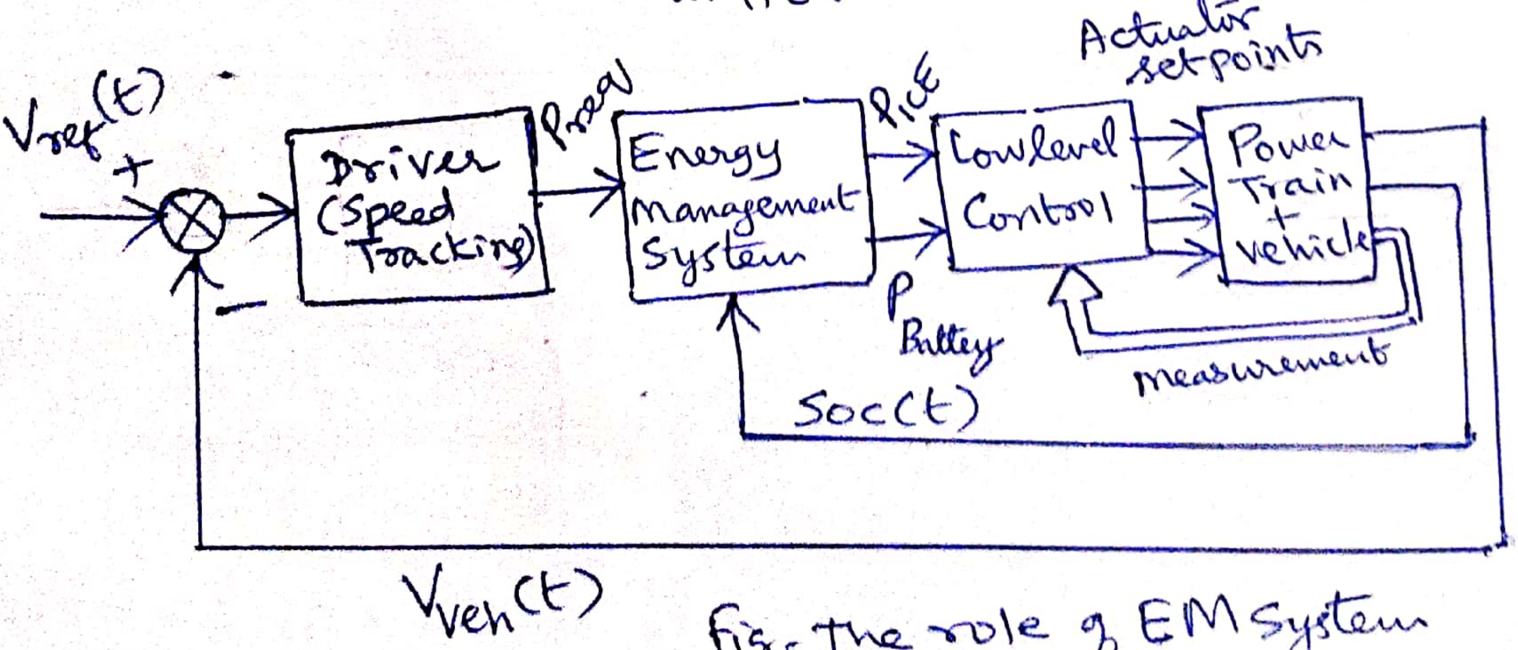


Fig- The role of EM System

Classification of Energy Management Strategies

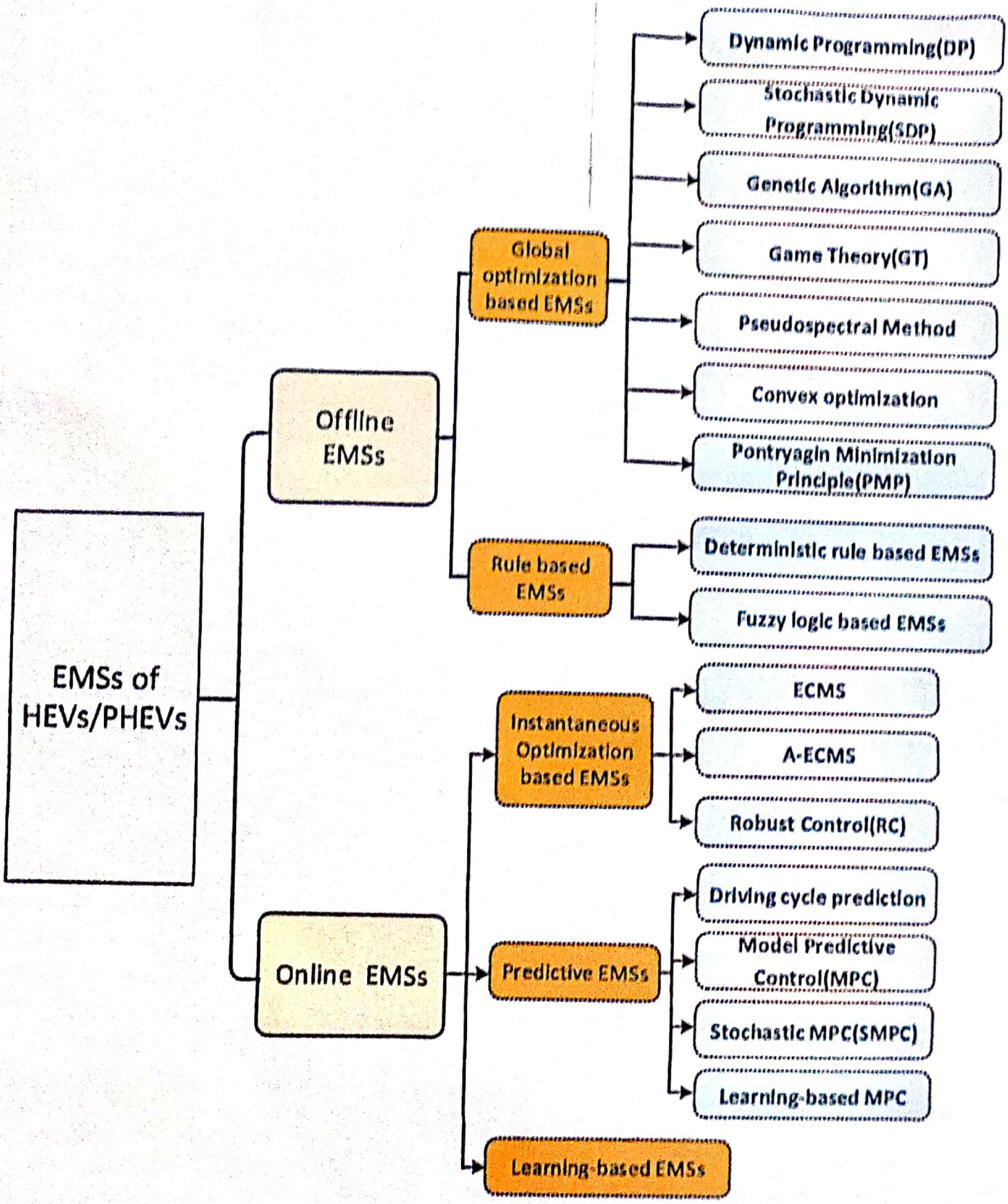
General Trends.

Rule based optimization Method

- Effective in realtime implementation
- Donot involve explicit minimization or optimization but rely on a set of rules to decide the value of control to apply at each time.
- Rules are based on heuristics, intuition or from the knowledge of the global optimal solution with the optimization algorithm for the mathematical models.

Model based optimization Method.

- In this, the optimum actuator set points are calculated by the global optimization solution obtained by minimizing cost objective function for a fixed & known driving cycle & with the future driving informations.
- Cannot be used directly for real time implementation but can be used as a design tool.
- The design rules be used for online implementation (or) used as a bench mark solution to evaluate the Performance of other Control Strategies.


EMSs of HEVs/PHEVs
Offline EMSs
Global optimization based EMSs
Dynamic Programming(DP)
Stochastic Dynamic Programming(SDP)
Genetic Algorithm(GA)
Game Theory(GT)
Pseudospectral Method
Convex optimization
Pontryagin Minimization Principle(PMP)
Rule based EMSs
Deterministic rule based EMSs
Fuzzy logic based EMSs
Online EMSs
Instantaneous Optimization based EMSs
ECMS
A-ECMS
Robust Control(RC)
Predictive EMSs
Driving cycle prediction
Model Predictive Control(MPC)
Stochastic MPC(SMPC)
Learning-based MPC
Learning-based EMSs

② Rule based EMS:

- Commonly used EMS in light to mild HEVs.

Rule: 1

With a low power demand & low vehicle speed state & uses elec motor only.

Rule: 2

use both motor & ICE during high Power demand

Rule: 3

on highway or in stable driving use ICE only.

Rule: 4

Use the ICE for driving the vehicle and/or powering the motor to charge the battery depending on the SOC of the battery.

i, If SOC is too high then no need for charging the battery

(ii) If SOC is low then charge the battery as much as possible.

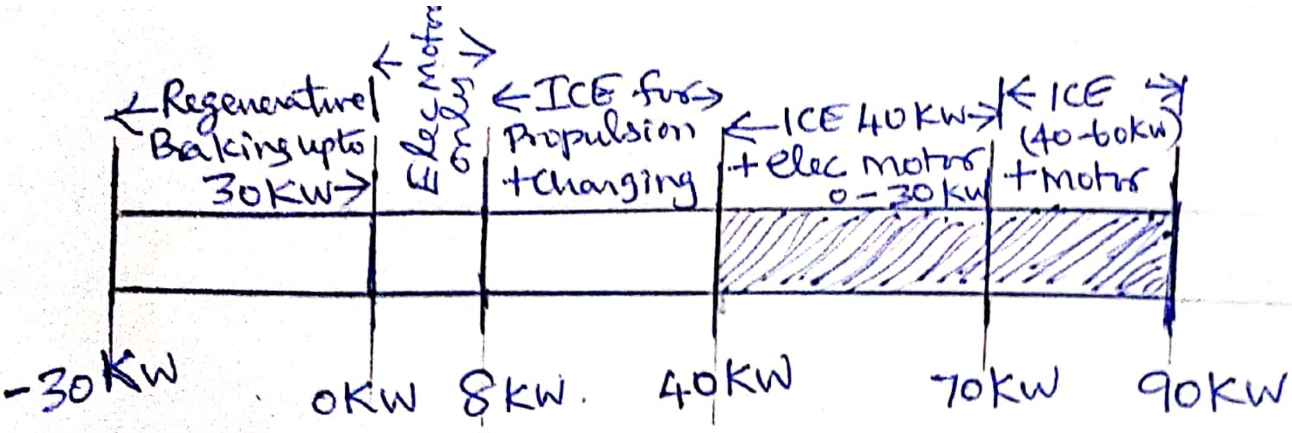


Fig: Power split for the vehicle's power demand based on rule based EMS.

Rule: 5

Maximum energy extract from regenerative (braking) energy.

Rule: 6

optimize the overall efficiency by adjusting the output power of the elec motor.

(i) If to enhance ICE to operate in higher efficiency range then elec motor provides Power.

(ii) Charge the battery if elec motor speed is in optimal range

(iii) Keep SOC of battery within 0.5-0.7 range & to have the battery with high efficiency & favourable battery life.

(iv) Charge the battery when vehicle power demand is low.

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Energy Management Issues

① Energy Consumption with respect to travel on road network.

② Usage & distribution of Charging facilities

③ Interaction of the vehicle with the Power grid.

① Energy Consumption of HEV:

- Focuses on
  - Zero emission
  - Improved efficiency.
- Developing accurate traffic models that can be used for both prediction & Control.
- Smart Traffic Management Systems (STMS) are developed rather than reacting to the traffic situations by
  - Recommending alternative paths for vehicle based on advanced routing technology.

- adjusting the timing & the phasing of green periods in traffic lights.
- Charging the speed limits or the recommended speeds.

- STMS are advantages for fuel cell HEVs, Conventional vehicles & Battery operated Electric vehicles (BEV)
- The user can select the shortest path, most economical path (no tolls) & minimum fuel path (less bends, no hill route etc)

② Usage & distribution of charging facilities

- Due to the long charging times of Fuel cell Elec vehicles (FCEV) it is advisible to have distribution of charging facilities
- During Journey even with fast charging may require atleast 15 minutes or more to get the Energy Storage System

to charge which is undesireable.

- Long queing at charging stations is also not preferred instead a reservation-based charging approach (which are updated periodically) is proposed.

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③ Interaction of the Vehicle with the Power grid.

- With the increased number of Plug-in-HEV in future will result in huge energy demand in the power grids which increases the stress in the grid. The stress in the grid result in voltage deviations, line overloading, or transformer overloading.
- At first the grids are designed to deal with peak power demand enabling the grid to have more spare capacity that will reduce the stress on the grid & also increases its efficiency.

- Secondly the plug-in-HEV are ideal for the load management as they are of highly flexible to the demands.

Comparison of various HEV Control Strategies

Control Strategy	Description	Advantages	Disadvantages
Electrically Peaking Hybrid Concept	• Elec motor Provides acceleration & deceleration Power. • ICE provides average load Power in drive cycle.	• ICE at high speeds reduces emission & fuel economy • Performance Comparable to Conventional Vehicles.	• The power Provided by the batteries is Significant requires more batteries Thus more weight
Thermostat or ON/OFF Strategy	• Propulsion depends on SOC of the battery • High SOC - Motor operates • low SOC - ICE operates	• Increases fuel economy of a series hybrid vehicle	• Produces deep cycles in the battery damaging the battery

Scanned with CamScanner

Power - follower Series Hybrid Control Strategy	• The ICE Power varies directly with the tractive Motor power, but it is higher by a SOC dependent factor to allow for losses in the gen/battery	• Better fuel economy • ICE immediately follows tractive Power requirements, giving better performance.	• No emissio benefits over ICE based vehicles & is chosen only for its fuel economy Characteristi
Fuzzy Logic Control	• ICE operated in limited fuel use strategy or efficiency strategy • Motor operates at low Speed	• SOC in limits • Tolerant to imprecise measurements & Component variability	• High fuel Consumptio because ICE is operated in high torque region.

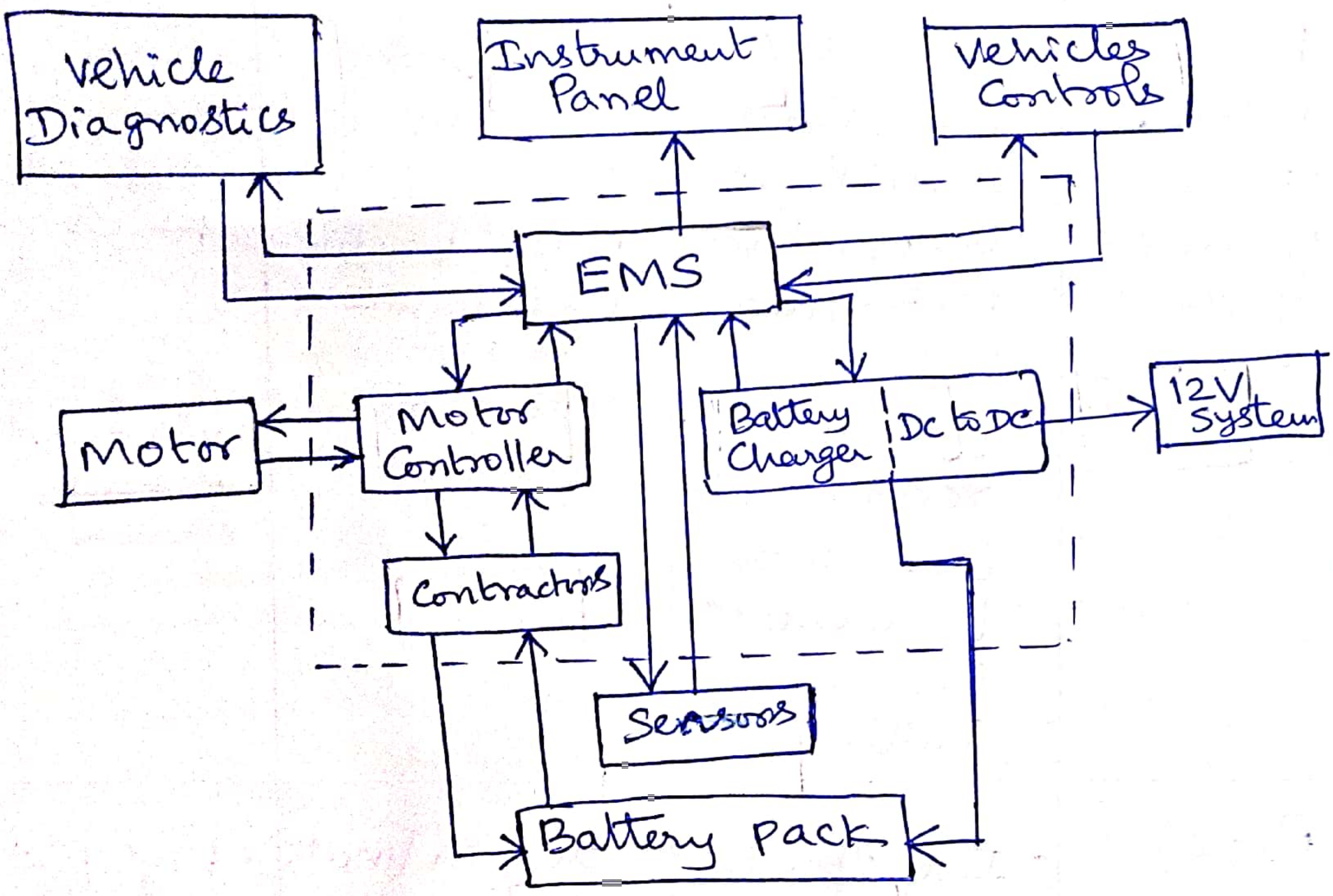

Fig. Energy Management System

- Inorder to maximize the utilization of on-board stored energy Energy Management Systems/ strategies are required.
- EMS required to
  - optimize the system energy flow.
  - Predict the remaining available energy
  - Suggest more efficient driving behaviour
  - To aquire regenerative energy efficiently
  - To choose the battery charging algorithms
  - To detect defective Components/incorrect operation
  - To ensure temperature Control

③ Determination of the operational Points for ICE in HEV

- As the power supplied by ICE affects the fuel economy and emission of HEV it is necessary to find the optimal operational points based on the HEV's driving characteristics.
- Two-step optimization method is adopted to detemine the above.
- The Operational points (OP) for the ICE in HEV which are responsible to determine the trade-off between emissions & the fuel consumption rate.
- The optimal Operational points of the ICE in HEV be

$$OP^* \in \text{possible } OPs. \rightarrow ①$$

Minimizing the following objective functions

$$J_1 = a_1 \cdot \text{fuel} + a_2 \cdot NO_x + a_3 \cdot CO + a_4 HC + a_5 PM \rightarrow ②$$

$$J_2 = b_1 J_{p1} + b_2 \cdot J_{p2} + \dots b_n J_{pm} \rightarrow ③$$

where a_1 to a_5 are the weighting factors corresponding to the relative importance between fuel economy & emission.

fuel → fuel Consumption

NO_x → Nitrogen oxides

CO → Carbon Monoxide.

HC → Hydrocarbon.

PM → Particle matter

b_1 to b_n → weighting factors corresponding to the frequency of power level at which the ICE operates

J_{P1} → objective function value at which ICE operates in idle state (Zero power output.

J_{Pn} → objective function value at which ICE operates at n^{th} power level.

Subject to the Constraints

$$OP_1 \leq OP_2 \leq \cdots \leq OP_n \longrightarrow ④$$

where OP_1 → operational speed of ICE at zero output power (idle state)

OP_n → operational speed of ICE at which ICE outputs its maximum power.

Two-step optimization Algorithm for optimal operational point determination.

- First step uses the golden section search algorithm to obtain the local optimal operational point at each specific operational power level of the ICE by minimizing the objective function J_1 eqn ② without considering the objective function J_2 eqn ③ or the constraints eqn ④;
- Second step, then dynamic programming is employed to obtain the global minimum by minimizing the objective function J_2 subject to the operational constraints.

Algorithm:-

1. Determine how many operational points need to be calculated based on the operational specification of the ICE.
2. calculate the values of the objective function J_1 reflecting the different

operational speeds at the given operational Power level.

3. Find the optimal operational speed which minimizes the objective function J_1 using an optimization Method like Golden Section Searching Method.

4. Obtain the global optimal points by minimizing the objective function J_2 considering the constraints using Dynamic programming methods.

Cost Function based optimal Energy Management Strategy.

- The optimal distribution of the vehicles Power demand have to be met out by the ICE and Motor apart from the Energy storing Systems.
- The Power sharing decision affects the overall performance of the vehicle, including drivability, fuel economy + emission.

- Various strategies were proposed to achieve the optimal fuel economy & emissions like realtime optimization algorithm for fuel economy & emissions, intelligent energy management methods & cost function based strategies

Mathematical Cost function modelling for optimal Energy Management in HEVs.

Cost function (objective function)

$$J = J_{ICE\,cost} + J_{motor\,cost} + J_{\substack{battery\\life\\cost}} + J_{\substack{Energy\\balance\\cost}}$$

$$= C_{fuel} \cdot P_{ICE} + C_{elec} \cdot P_{motor} + C_{\substack{battery\\life}} \cdot P_{motor} + C_{\substack{Energy\\balance}} \cdot P_{motor}.$$

$$= C_{fuel} \cdot P_{ICE} + (C_{elec} + C_{\substack{battery\\life}} + C_{\substack{Energy\\balance}}) P_{motor}. \longrightarrow ①$$

Subject to the Constraints

$$\left.\begin{aligned} P_{reqd\text{-}vehicle} &= P_{ICE} + P_{motor} \\ P_{ICE} &\geq 0 \end{aligned}\right\} \longrightarrow ②$$

Operational Constraints

- **Constraints from the ICE**
  - Maximal propulsion power is a function of its speed

$$P_{max,ICE} = f(speed)$$

- **Constraints from the elec Motor**
  - Maximal propulsion power of the elec motor is a function of temperature, speed, and torque of the motor under the given operational conditions

$$P_{max,\underset{prop}{motor}} = f(Temp, Speed, Torque)$$

  - Maximal Regenerative Power of the elec motor is also related to the temperature, speed and torque of the motor under the given operational conditions.

$$P_{max.regen.motor} = f(Temp, Speed, Torque)$$

- **Constraints from the Energy Storage Systems (ESS)**

- **Maximal charging power availability** of ESS is a function of temperature, SOC, State of Health (SOH) under the given operational conditions.

$$P_{\text{max char batt}} = f(\text{Temp}, \text{SOC}, \text{SOH})$$

- **Maximal discharging power availability** of ESS is also a function of temp, SOC, SOH

$$P_{\text{max dischar batt}} = f(\text{Temp}, \text{SOC}, \text{SOH})$$

where

$$C_{\text{fuel}} = f(\text{Temperature}_{\text{ICE}}, \text{Torque}_{\text{ICE}}, \text{Speed}_{\text{ICE}})$$

weighting factors.

$$C_{\text{elec}} = f(C_{\text{fuel}}, \text{Efficiency}_{\text{Motor}}\ \text{Efficiency}_{\text{batt}})$$

$$= \frac{\text{Mini}(C_{\text{fuel}})}{\eta_{\text{motor}} \cdot \eta_{\text{battery}}}$$

Celec is the weight factor for the elec energy cost, which is normalized & equalized to the fuel cost of ICE.

The normalization is based on the best fuel rate of the ICE at the current operational speed and efficiencies of the motor & battery

Efficiency of the battery η_{batt}

$$\eta_{batt} = \eta_{discharge} \text{ if } P_{motor} \leq 0$$

$$\eta_{batt} = \eta_{charge} \text{ if } P_{motor} > 0$$

& η_{motor} is the efficiency of the motor/inverter system under current operational condition

$$C_{\substack{battery\\life}} = f(SOC, Temperature, P_{motor})$$

$$C_{\substack{Energy\\Balance}} = f(SOC, Temperature, P_{motor})$$

— x —

④ Optimization Problem:

objective Function

$$J = C_{fuel} \cdot P_{ICE} + (C_{elec} + C_{\substack{batt\\life}} + C_{\substack{Energy\\Balance}}) P_{motor}$$

Subject to Constraints

$$P_{ICE} + P_{motor} = P_{\substack{demand\\Vehicle}}$$

under the Constraints

1. If $P_{\substack{demand\\Vehicle}} \geq 0$

$$P_{ICE} \leq P_{max, ICE}$$

$$P_{motor} \leq \min(P_{\substack{max\ discharge\\batt}} , P_{\substack{max\ prop\\motor}})$$

2 If $P_{\substack{demand\\Vehicle}} < 0$

$$P_{motor} > Max(P_{\substack{max\ Charg\\batt}} , P_{\substack{max\ regen\\motor}})$$

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Cycle Pattern Recognition based optimal Energy Management Strategy (EMS)

The previously discussed problem i.e

- optimal operational point determination for ICE in HEV
- Cost function based optimal (EMS) (mathematical modelling)

the decision is based only on the Current vehicle operating Conditions without Considering the driving cycle or driver's driving style.

- But in this the driving cycles/style pattern recognition algorithm is used.
- The vehicle's present requirement like speed, torque & battery system operational Conditions, Vehicle's environmental Conditions are Considered & the optimal split power decision between ICE & motor are optimized using Dynamic Programming

Programming optimization algorithm & the predicted future driving power profile output from the pattern recognition algorithm is adopted.

Driving Cycle/Style Pattern Recognition Algorithm.

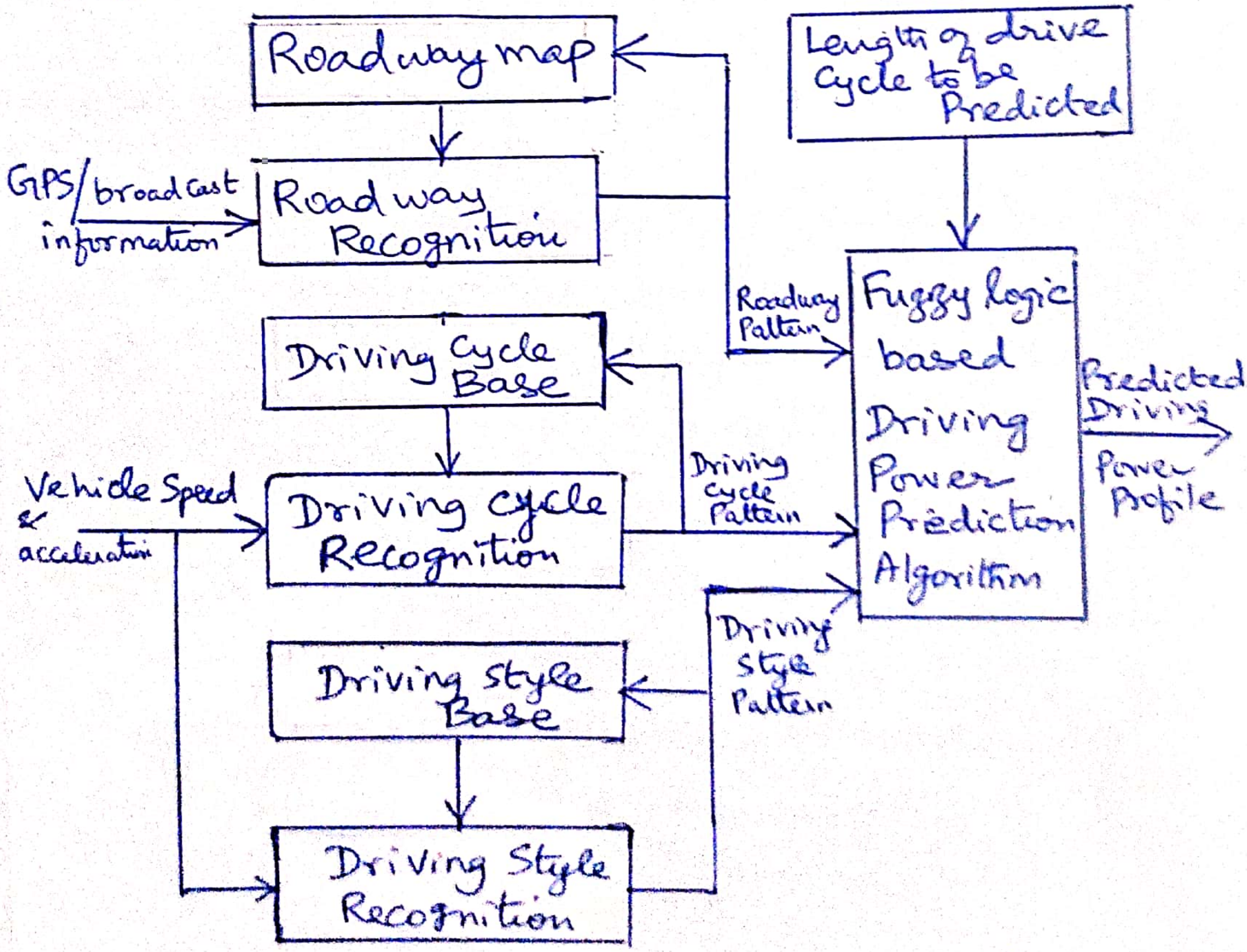

Fig: Entire Pattern Recognition Algorithm

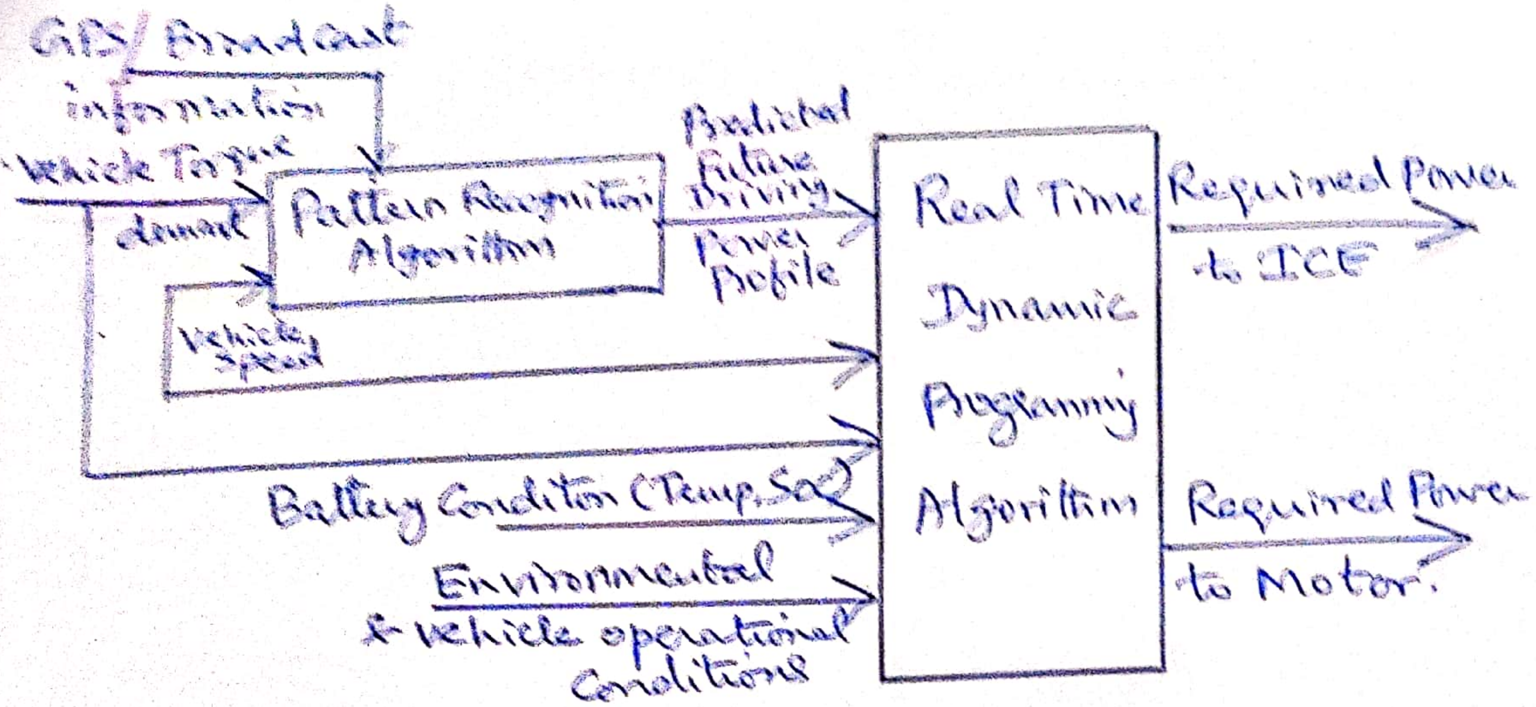

Fig. Optimal EMS with a pattern Recognition Algorithm.

- The entire pattern recognition algorithm consists of roadway recognition, driving cycle pattern recognition & driving style recognition algorithm.
- The recognized patterns are fed to the fuzzy logic based driving power prediction algorithm to generate the future driving power profile in the given prediction horizon period of time.

↘

) Roadway Recognition (RwR) Algorithm

- This is adopted to identify the current roadway conditions combined with the traffic congestion situation based on GPS or broadcasting informations & stored street maps.
- The roadway map is updated to the previous roadway recognition.

② Driving Cycle Recognition (DCR) Algorithm

- This algorithm works out the current driving pattern based on the vehicle's speed and acceleration and on stored cycle data.
- The acquired information about the driving pattern & parameter characteristics used by the fuzzy logic based driving power prediction algorithm to predict the vehicle's power demand in a certain period of time.

③ Driving Style Recognition (DSR) Algorithm

- Driving style has a strong influence on fuel economy & emissions.
- There are three types of driving style: light, mild & aggressive.
- DSR algorithm is designed to provide driving style information to the Power prediction Algorithm based on the current and historical data to Predict the vehicle's power demand in a certain period of time.

④ Fuzzy Logic based Vehicle Power demand Prediction.

- The Roadway driving pattern, driving cycle pattern, driving style pattern & the desired time length of the prediction horizon as inputs to the Fuzzy logic based prediction algorithm.

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Determination of the Optimal Energy Distribution in HEV.

Objective function;

Let the Cost function be $[J]$

$$[J] = J_{ICE} = (\text{fuel Cost}) . P_{ICE}$$

Subject to the Constraints

- Emission:
$$0 \leq NO_x \leq \max$$
$$0 \leq CO \leq \max$$
$$0 \leq PM \leq \max$$
- Discharge from battery:
$$\min \leq [SOC_{new} - SOC_{old}]^2 \leq \max$$

Augmented Objective function

$$J = \left[\lambda J_{ICE} + \lambda_1 NO_x + \lambda_2 CO + \lambda_3 PM + \lambda_4 [SOC_{new} - SOC_{old}]^2\right]$$

where $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ are Lagrangian Multiplie

↘

The necessary and sufficient condition for minimizing the augmented objective functions are. $\frac{\partial J}{\partial \lambda} = 0$

$$\frac{\partial J}{\partial \lambda_1} = 0$$

$$\frac{\partial J}{\partial \lambda_2} = 0$$

$$\frac{\partial J}{\partial \lambda_3} = 0$$

$$\frac{\partial J}{\partial \lambda_4} = 0$$

—x—

EEPESCN	ELECTRICAL AND HYBRID VEHICLES	L	T	P	C
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Unit - I: Introduction

Conventional Vehicles: Basics of vehicle performance, vehicle power source characterization, transmission characteristics, mathematical models to describe vehicle performance.

Unit-II: Hybrid Vehicles

Introduction to Hybrid Electric Vehicles: History of hybrid and electric vehicles, social and environmental importance of hybrid and electric vehicles, impact of modern drive-trains on energy supplies.

Hybrid Electric Drive-trains: Basic concept of hybrid traction, introduction to various hybrid drive-train topologies, power flow control in hybrid drive-train topologies, fuel efficiency analysis.

Unit - III: Electric Trains

Electric Drive-trains: Basic concept of electric traction, introduction to various electric drive-train topologies, power flow control in electric drive-train topologies, fuel efficiency analysis. Electric Propulsion unit: Introduction to electric components used in hybrid and electric vehicles, Configuration and control of DC Motor drives, Configuration and control of Induction Motor drives, configuration and control of Permanent Magnet Motor drives, Configuration and control of Switch Reluctance Motor drives, drive system efficiency.

Unit - IV: Energy Storage

Energy Storage: Introduction to Energy Storage Requirements in Hybrid and Electric Vehicles, Battery based energy storage and its analysis, Fuel Cell based energy storage and its analysis, Super Capacitor based energy storage and its analysis, Flywheel based energy storage and its analysis, Hybridization of different energy storage devices. Sizing the drive system: Matching the electric machine and the internal combustion engine (ICE), Sizing the propulsion motor, sizing the power electronics, selecting the energy storage technology, Communications, supporting subsystems

Unit - V: Energy Management Strategies

Energy Management Strategies: Introduction to energy management strategies used in hybrid and electric vehicles, classification of different energy management strategies, comparison of different energy management strategies, implementation issues of energy management strategies. Case Studies: Design of a Hybrid Electric Vehicle (HEV), Design of a Battery Electric Vehicle (BEV).

Text / References:

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EEPE605	ELECTRICAL AND HYBRID VEHICLES	L	T	P	C
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Course Objectives:

- To understand the fundamental concepts, principles, analysis and design of hybrid and electric vehicles.
- To acquire knowledge on the social and environmental importance, basic concepts and configuration of hybrid EV and electric driven train.
- To study various types of electric machines and energy storage devices used in hybrid and electric drive and to study the configuration and control of various electrical machines.
- To learn in detail about the Energy Storage Requirements in Hybrid and Electric Vehicles apart from the communication and supporting subsystems used.
- To understand the design of different energy management strategies, implementation issues in hybrid electric vehicle and battery electric vehicle.

Unit - I: Introduction

Conventional Vehicles: Basics of vehicle performance, vehicle power source characterization, transmission characteristics, mathematical models to describe vehicle performance.

Unit-II: Hybrid Vehicles

Introduction to Hybrid Electric Vehicles: History of hybrid and electric vehicles, social and environmental importance of hybrid and electric vehicles, impact of modern drive-trains on energy supplies.

Hybrid Electric Drive-trains: Basic concept of hybrid traction, introduction to various hybrid drive- train topologies, power flow control in hybrid drive-train topologies, fuel efficiency analysis.

Unit - III: Electric Trains

Electric Drive-trains: Basic concept of electric traction, introduction to various electric drive-train topologies, power flow control in electric drive-train topologies, fuel efficiency analysis. Electric Propulsion unit: Introduction to electric components used in hybrid and electric vehicles, Configuration and control of DC Motor drives, Configuration and control of Induction Motor drives, configuration and control of Permanent Magnet Motor drives, Configuration and control of Switch Reluctance Motor drives, drive system efficiency.

Unit - IV: Energy Storage

Energy Storage: Introduction to Energy Storage Requirements in Hybrid and Electric Vehicles, Battery based energy storage and its analysis, Fuel Cell based energy storage and its analysis, Super Capacitor based energy storage and its analysis, Flywheel based energy storage and its analysis, Hybridization of different energy storage devices. Sizing the drive system: Matching the electric machine and the internal combustion engine (ICE), Sizing the propulsion motor, sizing the power electronics, selecting the energy storage technology, Communications, supporting subsystems

Unit - V: Energy Management Strategies

Energy Management Strategies: Introduction to energy management strategies used in hybrid and electric vehicles, classification of different energy management strategies, comparison of different energy management strategies, implementation issues of energy management strategies. Case Studies: Design of a Hybrid Electric Vehicle (HEV), Design of a Battery Electric Vehicle (BEV).

Text / References:

1. C. Mi, M. A. Masrur and D. W. Gao, “Hybrid Electric Vehicles: Principles and Applications with Practical Perspectives”, John Wiley & Sons,2011.
2. S. Onori, L. Serrao and G. Rizzoni, “Hybrid Electric Vehicles: Energy Management Strategies”, Springer,2015.
3. M. Ehsani, Y. Gao, S. E. Gay and A. Emadi, “Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design”, CRC Press,2004.
4. T. Denton, “Electric and Hybrid Vehicles”, Routledge,2016.
5. A.K.Babu, "Electric & Hybrid Vehicles", Khanna Publishers, New Delhi 2020
6. Anupam Singh, "Electric Vehicles: And the end of ICE Age", Adhyyan Books, New Delhi 2020.

Course Outcomes:

At the end of this course, students will demonstrate the ability to

1. Understand the models to describe hybrid vehicles and their performance.
2. Identify the different possible strategies in hybridization of EV.
3. Know the various topologies of electric drive and its control.
4. Familiarize the different strategies related to energy storage systems.
5. Gain knowledge about different energy management strategies adopted for EV.

Mapping with Program Outcomes

	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2	PSO3
CO1	3	2					3	1				2	3		
CO2	3	2	2	2		2	2		2		2	2		2	
CO3	3	2	3		2	2		1	2		2		2		
CO4	3	2	2	2		2	2	2		2		2		2	3
CO5	3	3		2	3	2		2	2		3	2		2	3