III Year B. Tech. EEE II-Semester

Electric & Hybrid Vehicles
Course Code: PE116CW 3
(Professional Elective-II)

Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

Unit1:
Introduction to Hybrid Electric vehicles

Introduction:

- Introduction to Hybrid Electric vehicles:
  - History of Hybrid Electric Vehicles
  - Social and environmental importance of Hybrid and Electric vehicles
- Vehicle Fundamentals:
  - Vehicle Resistance
  - Dynamic Equation
  - **Tire-Ground Adhesion and Maximum Tractive effort**
  - **Power Train Tractive effort and Vehicle speed**
  - **Vehicle power Plant and Transmission Characteristics**
  - Vehicle Performance
  - Operating Fuel Economy braking Performance

Tire-Ground Adhesion and Maximum Tractive effort

- When Tractive Effort of the vehicle > Maximum tractive effort

Then drive wheels spin on the ground. (This happens when Tractive effort exceeds its maximum limit due to the adhesive capability between tire and ground.)

- Adhesive capability between tire and ground is the main limitation in vehicle performance (in most of the cases where the road is wet, icy, snow-Covered, oily or soft soil roads)
- In this case, tractive torque in drive wheel would cause the wheel to slip on the ground. So, in this case, The maximum tractive effort on the driven wheel depends on the longitudinal force that the adhesive capability between the tire and ground can supply, rather than the maximum torque that the engine can supply.
- As per the Experimental results on various types of ground, the maximum tractive effort of the drive wheel closely relates to the slipping of the running wheel.

This is also true on a good paved, dry road where the slipping is very small due to the elasticity of the tire.

Slip

Slip. S of the tire is defined as

$$\mathbf{S}= \left(\mathbf{1}-\frac{\boldsymbol{V}}{\boldsymbol{r\omega}}\right)\boldsymbol{*}\ \mathbf{100\%}\ = \left(1-\frac{r_e}{r}\right) * 100\% \text{ --(1)}$$

- where V → translatory speed of the tire center,
- ω → angular speed of the tire,
- r → rolling radius of the free rolling tire,
- and *re* → effective rolling radius of the tire,
- Effective rolling radius: Ratio of the translatory speed of the tire center to the angular speed of the tire.

In traction, the speed V is less than $r\omega$, therefore, the **slip of the tire** has a positive value **between 0 and 1.0.**

During braking, however, the tire slip would be defined as

$$\text{S}= \left(1-\frac{r\omega}{V}\right) * 100\% = \left(1-\frac{r}{r_e}\right) * 100\% \text{ --(2)}$$

Positive value between 0 and 1 similar to traction.

Slip

- The maximum traction effort of a tire corresponding to a certain tire slip is

$$F_{tmax} = P\mu \text{ – (3)}$$

μ → Tractive effort coefficient

P→ Vertical load of the tire

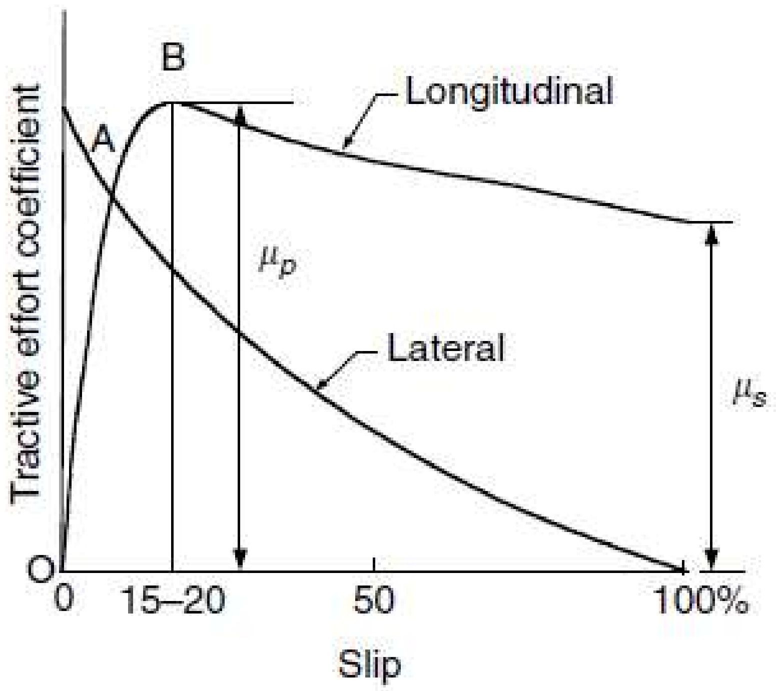


Fig1. Variation of tractive effort coefficient with longitudinal slip of a tire

- In the small slip range (section OA in Figure), the tractive effort is almost linearly proportional to the slip value.
- This small slip is caused by the elasticity of the tire rather than the relative slipping between the tire and the ground at the contact patch, as shown in Figure 2.7.
- When a tractive torque is applied to the tire, a tractive force is developed at the tire–ground contact patch. At the same time, the tire tread in front and within the contact patch is subjected to compression. A corresponding shear deformation of the side wall of the tire is also developed. As tread elements are compressed before entering the contact region, the distance that the tire travels will be less than the distance in a free rolling tire. Because of the nearly linear elastic property of the tire, the tractive effort–slip curve is almost linear.
- A further increase in wheel torque and tractive force results in part of the tire tread sliding on the ground.
- Under these circumstances, the relationship between tractive force and slip is nonlinear.
- This corresponds to section AB of the curve as shown in Figure 2.6. The peak tractive effort is reached at a slip of 15–20%.
- A further increase in slip beyond this results in an unstable condition. The tractive effort coefficient falls rapidly from the peak value to the purely sliding value as shown in Figure 2.6.
- For normal driving, the slip of the tire must be limited in a range less than 15–20%.

Behavior of a tire under the action of driving torque

Average Values of Tractive Effort Coefficient on Various Roads

Surface	Peak Values, μ_p	Sliding Values, μ_s
Asphalt and concrete (dry)	0.8–0.9	0.75
Concrete (wet)	0.8	0.7
Asphalt (wet)	0.5–0.7	0.45–0.6
Grave	0.6	0.55
Earth road (dry)	0.68	0.65
Earth road (wet)	0.55	0.4–0.5
Snow (hard packed)	0.2	0.15
Ice	0.1	0.07

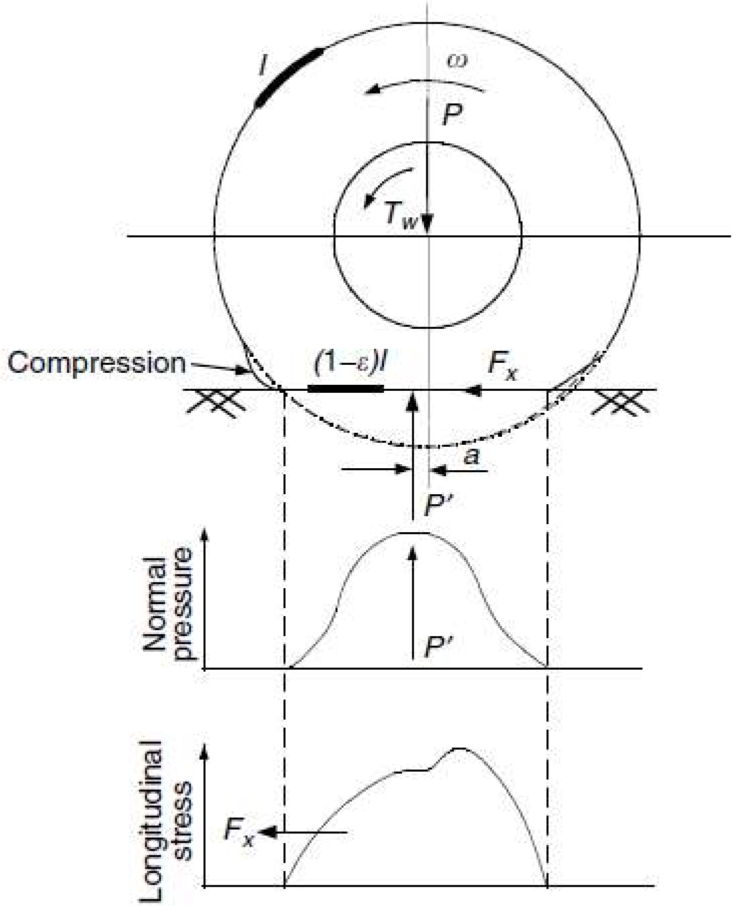


FIG 2 Behavior of a tire under the action of driving torque

Power Train Tractive Effort and Vehicle Speed

An automotive power train, as shown in Figure 2.8, consists of
a power plant (engine or electric motor),
a clutch in manual transmission or a torque converter in automatic transmission,
a gearbox (transmission),
final drive,
differential,
drive shaft, and
driven wheels.

The torque and rotating speed of the power plant 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 transmission to couple the gearbox to or decouple it from the power plant. The torque converter in automatic transmission is a hydrodynamic device, functioning as the clutch in manual transmission with a continuously variable gear ratio.
The gearbox supplies a few gear ratios from its input shaft to its output shaft for the power plant torque–speed profile to match the requirements of the load.
The final drive is usually a pair of gears that supply a further speed reduction and distribute the torque to each wheel through the differential.

Power Train Tractive Effort and Vehicle Speed

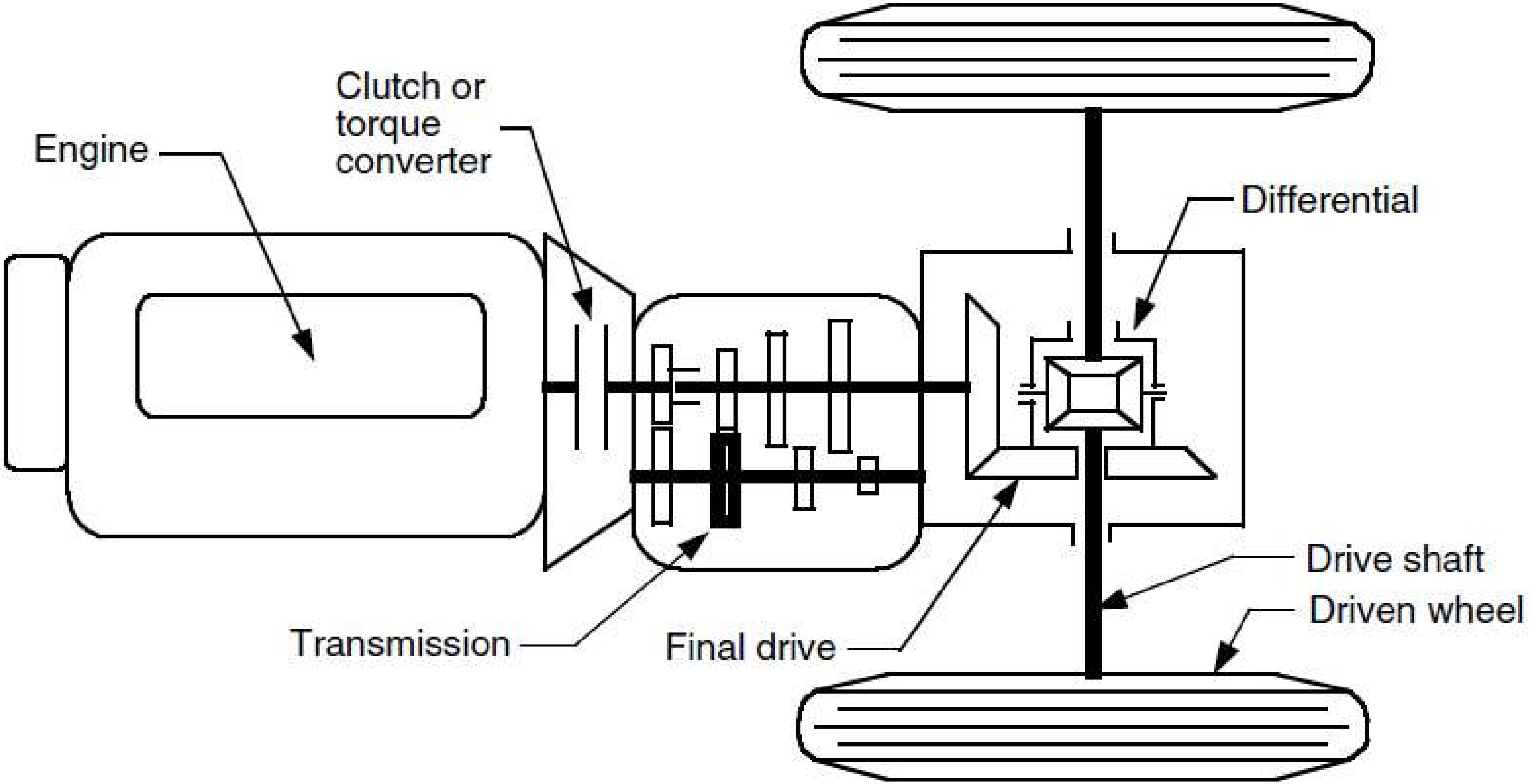


Fig3. Conceptual illustration of an automobile power train

Power Train Tractive Effort and Vehicle Speed

- The torque on the driven wheels, transmitted from the power plant, is expressed as
- $T_\omega = i_g i_o \eta_t T_p$ --1
- i_g → Gear ratio of the transmission ➔ $i_g = \frac{N_{in}}{N_{out}}$ --2
- N_{in} → Rotating Speed
- N_{out} → $Output\ rotating\ speed$
- i_o → Gear ratio of the final drive
- η_t → Efficiency of the drive line from the power plant to the driven wheels
- T_p → Torque output from the power plant

Power Train Tractive Effort and Vehicle Speed

- The tractive effort on the driven wheels, can be expressed as
- $F_t = \frac{T_w}{r_d} = \frac{i_g i_o \eta_t T_p}{r_d}$ --3
- The friction in the gear teeth and the friction in the bearings create losses in mechanical gear transmission.
- The following are representative values of the mechanical efficiency of various components:
- Clutch: 99%
- Each pair of gears: 95–97%
- Bearing and joint: 98–99%
- The total mechanical efficiency of the transmission between the engine output shaft and drive wheels is the product of the efficiencies of all the components in the driveline.
- As a first approximation, the following average values of the overall mechanical efficiency of a manual gear-shift transmission may be used:
- Direct gear: 90%
- Other gear: 85%
- Transmission with a very high reduction ratio: 75–80%

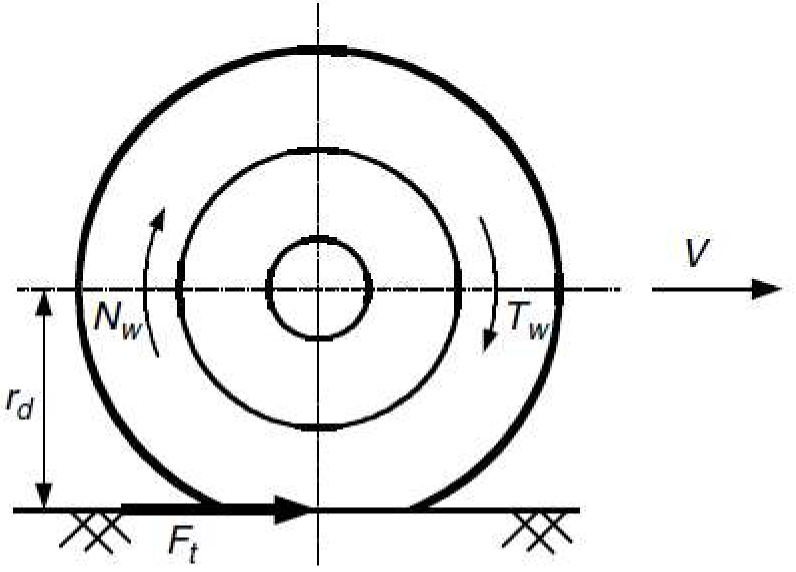


Fig 4. Tractive effort and torque on a driven wheel

Power Train Tractive Effort and Vehicle Speed

The rotating speed (rpm) of the driven wheel can be expressed as

$$N_w = \frac{N_p}{i_g i_0} \text{ --- } 4$$

N_p → Output rotating speed (rpm)

Translational speed of the wheel center or vehicle speed

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

Now substituting equ 5 in equ 4 we get

$$V = \frac{\pi N_p r_d}{30 i_g i_0} \text{ -- } 6$$

Vehicle Power Plant and Transmission Characteristics

There are two limiting factors to the maximum tractive effort of a vehicle.

- Tire–ground contact can support $F_{tmax} = \frac{\mu M_v g cos\alpha [L_b + \mu_r (h_g - r_d] / L}{\left(1+\frac{h_g}{L}\mu\right)}$ → 7

And $F_{tmax} = \frac{\mu M_v g cos\alpha [L_a + \mu_r (h_g - r_d] / L}{\left(1+\frac{h_g}{L}\mu\right)}$ → 8

- The other is the tractive effort the torque with given driveline gear ratios can provide t the power plant

$$F_t = \frac{T_w}{r_d} = \frac{i_g i_o \eta_t T_p}{r_d} \rightarrow 9$$

- The smaller of these two factors will determine the performance potential of the vehicle. For on-road vehicles, the performance is usually limited by the second factor. In order to predict the overall performance of a vehicle, its power plant and transmission characteristics must be taken into consideration.

Power Plant Characteristics

- For vehicular applications, the ideal performance characteristic of a power plant is the constant power output over the full speed range. Consequently, the torque varies with speed hyperbolically as shown in Figure 2.10.
- At low speeds, the torque is constrained to be constant so as not to be over the maxima limited by the adhesion between the tire–ground contact area.
- This constant power characteristic will provide the vehicle with a high tractive effort at low speeds, where demands for acceleration, drawbar pull, or grade climbing capability are high.

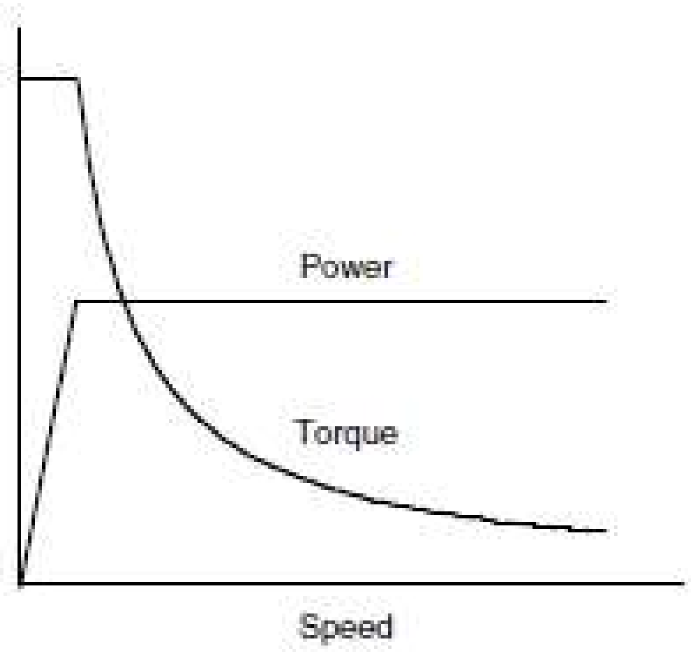


FIG 5: Ideal performance characteristics for a vehicle traction power plant

Power Plant Characteristics

- The internal combustion engine and electric motor are the most commonly used power plants for automotive vehicles till now.
- Basic features of the characteristics that are essential to predicating vehicle performance and driveline design are shown in the above figures.

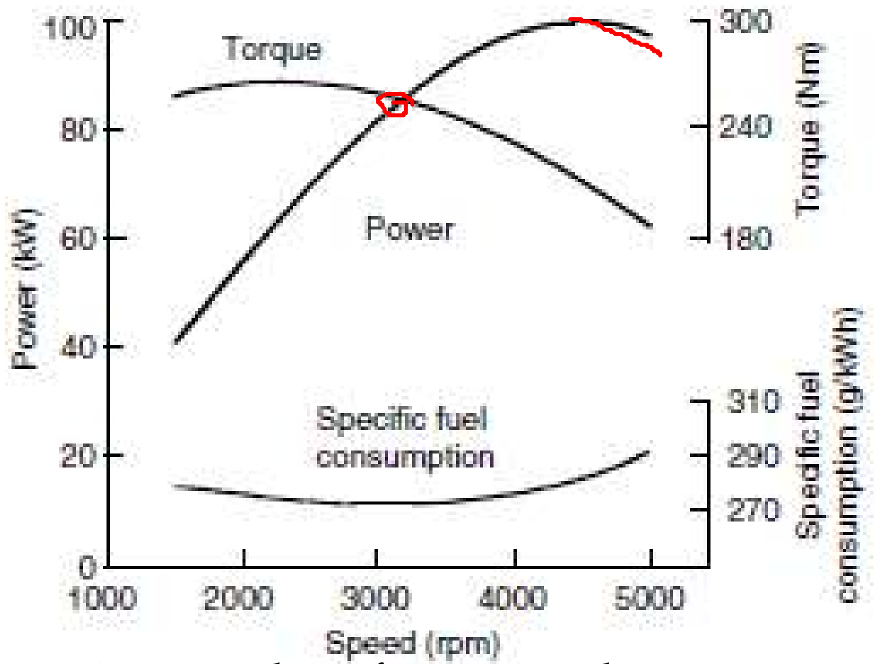


Fig6. Typical performance characteristics of gasoline engines

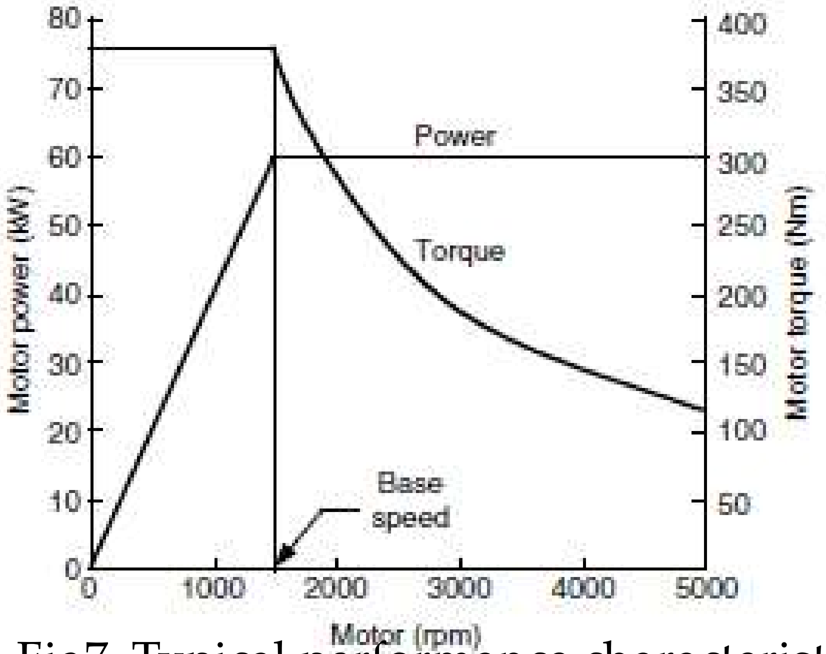


Fig7. Typical performance characteristics of electric motors for traction

Power Plant Characteristics

The ICE usually has torque–speed characteristics far from the ideal performance characteristic required by traction. It starts operating smoothly at idle speed.

Good combustion quality and maximum engine torque are reached at an intermediate engine speed. As the speed increases further, the mean effective pressure decreases because of the growing losses in the air-induction manifold and a decline in engine torque.

Power output, however, increases to its maximum at a certain high speed. Beyond this point, the engine torque decreases more rapidly with increasing speed. This results in the decline of engine power output.

- In vehicular applications, the maximum permissible speed of the engine is usually set just a little above the speed of the maximum power output.
- The internal combustion engine has a relatively flat torque–speed profile (compared with an ideal one), as shown in Fig 6.
- Consequently, a multigear transmission is usually employed to modify it, as shown in **FIG 8**.

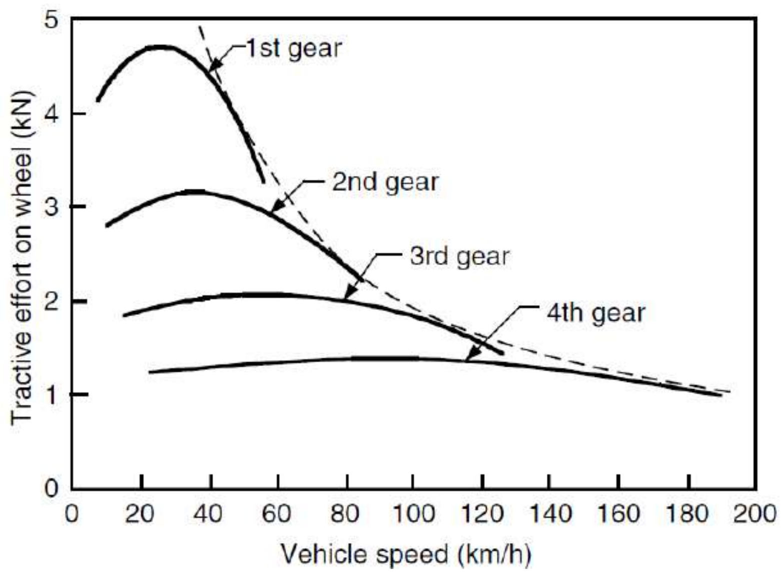


FIG 8: Tractive effort of internal combustion engine and a multigear transmission vehicle vs. vehicle speed

Power Plant Characteristics

- Electric motors, however, usually have a speed–torque characteristic that is much closer to the ideal, as shown in Fig 6. Generally, the electric motor starts from zero speed. As it increases to its base speed, the voltage increases to its rated value while the flux remains constant. Beyond the base speed, the voltage remains constant and the flux is weakened.
- This results in constant output power while the torque declines hyperbolically with speed. Since the speed–torque profile of an electric motor is close to the ideal, a single-gear or double-gear transmission is usually employed, as shown in **FIG 9**.

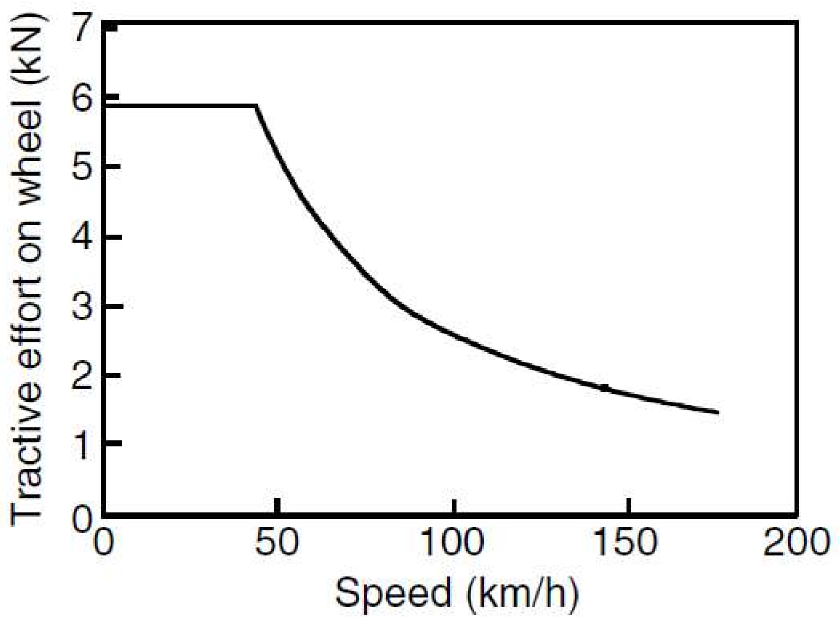


FIG 9: Tractive effort of a single-gear electric vehicle vs. vehicle speed

Transmission Characteristics

- The transmission requirements of a vehicle depend on the
  - characteristics of the power plant and
  - the performance requirements of the vehicle.
- The power plant of an electric vehicle will not need a multigear transmission.
- But ICE must have a multigear or continuously varying transmission to multiply its torque at low speed.
- Transmission includes all those systems employed for transmitting engine power to the drive wheels.
- . For automobile applications, basically transmission is two types
  - Manual gear transmission and
  - Hydrodynamic transmission

Transmission Characteristics: Manual Gear Transmission

- Manual gear transmission consists of a clutch, gearbox, final drive, and drive shaft as shown in Figure 3.
- The final drive has a constant gear reduction ratio or a differential gear ratio.

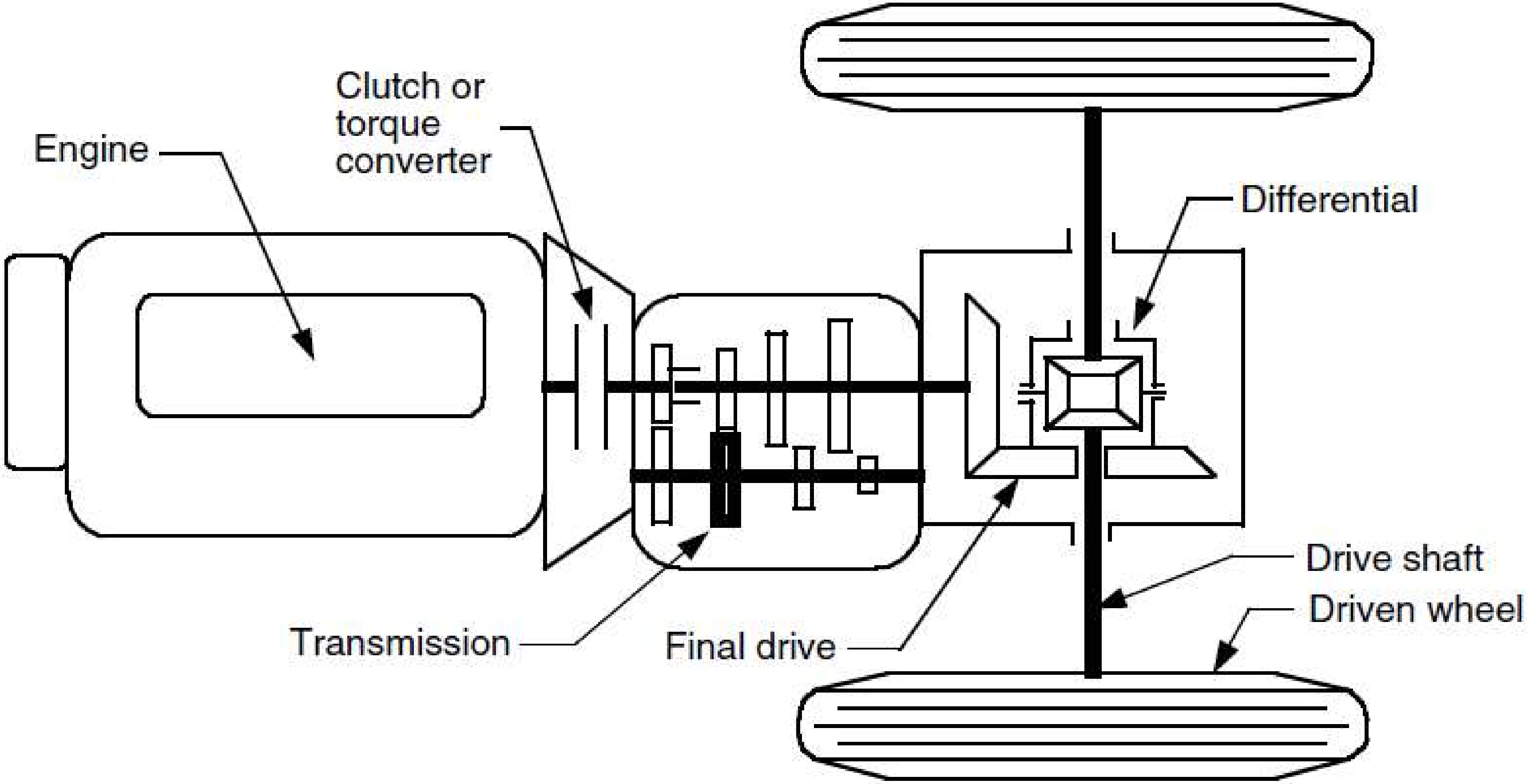


Fig3. Conceptual illustration of an automobile power train

Transmission Characteristics: Manual Gear Transmission

- The common practice of requiring direct drive (nonreducing) in the gearbox to be in the highest gear determines this ratio. The gearbox provides a number of gear reduction ratios ranging from three to five for passenger cars and more for heavy commercial vehicles that are powered with gasoline or diesel engines. The maximum speed requirement of the vehicle determines the gear ratio of the highest gear (i.e., the smallest ratio).
- On the other hand, the gear ratio of the lowest gear (i.e., the maximum ratio) is determined by the requirement of the maximum tractive effort or the gradeability.
- Ratios between them should be spaced in such a way that they will provide the tractive effort–speed characteristics as close to the ideal as possible, as shown in Figure 2.15.

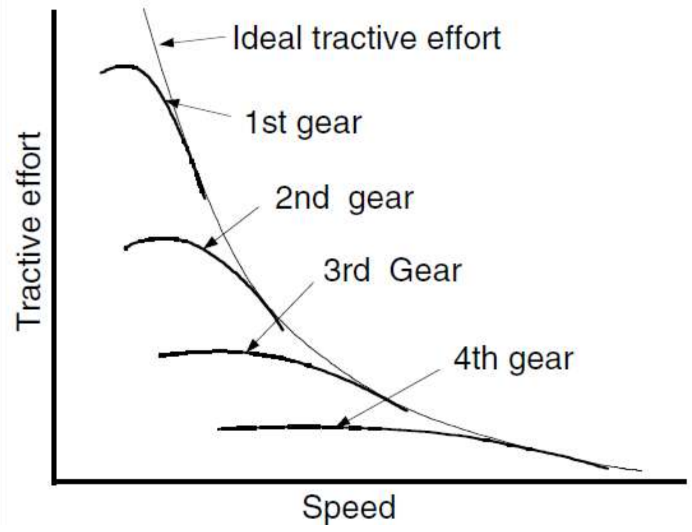


Fig 10. Tractive effort characteristics of a gasoline engine-powered vehicle

Transmission Characteristics: Manual Gear Transmission

- In the first iteration, gear ratios between the highest and the lowest gear may be selected in such a way that the engine can operate in the same speed range for all the gears.
- This approach would benefit the fuel economy and performance of the vehicle. For instance, in normal driving, the proper gear can be selected according to vehicle speed to operate the engine in its optimum speed range for fuel-saving purposes.
- In fast acceleration, the engine can be operated in its speed range with high power output.
- This approach is depicted in Fig 11. Where $i_{g1}, i_{g2}, i_{g3,}\, i_{g4}$ are the gear ratios for the first, second, third and fourth gear respectively.

$$\frac{i_{g1}}{i_{g2}} = \frac{i_{g2}}{i_{g3}} = \frac{i_{g3}}{i_{g4}} = K_g \text{ -- } 10$$

$$K_g = \sqrt{\frac{i_{g1}}{i_{g4}}} \text{ --}11$$

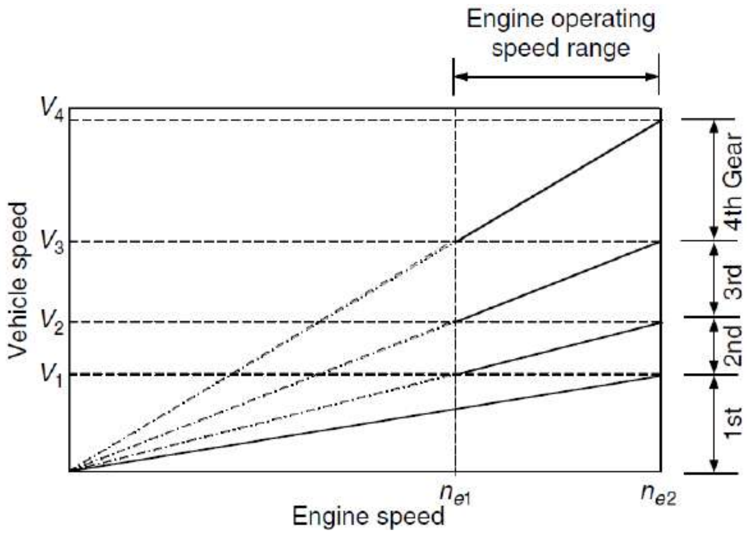


Fig 11. Demonstration of vehicle speed range and engine speed range for each gear

Transmission Characteristics: Manual Gear Transmission

In general, if the ratio of the highest gear, i_{gn} (smaller gear ratio) and the ratio of the lowest gear, i_{g1} (larger gear ratio) can be determined and the number of the gear n_g is known and the factor K_g can be determined as

$$K_g = \left(\frac{i_{g1}}{i_{gn}}\right)^{(n_g-1)} \rightarrow 12$$

And each gear ratio can be obtained by

$$i_{gn-1} = K_g\, i_{gn}$$
$$i_{gn-2} = K^{g^2}\, i_{gn}$$
$$i_{g2} = K^{g^{n-1}}\, i_{gn} \quad \rightarrow 13$$

Are suitable For passenger cars

For commercial vehicles the gear ratios in gearbox are arranged as $\frac{i_{g1}}{i_{g2}} > \frac{i_{g2}}{i_{g3}} > \frac{i_{g3}}{i_{g4}} \rightarrow 14$

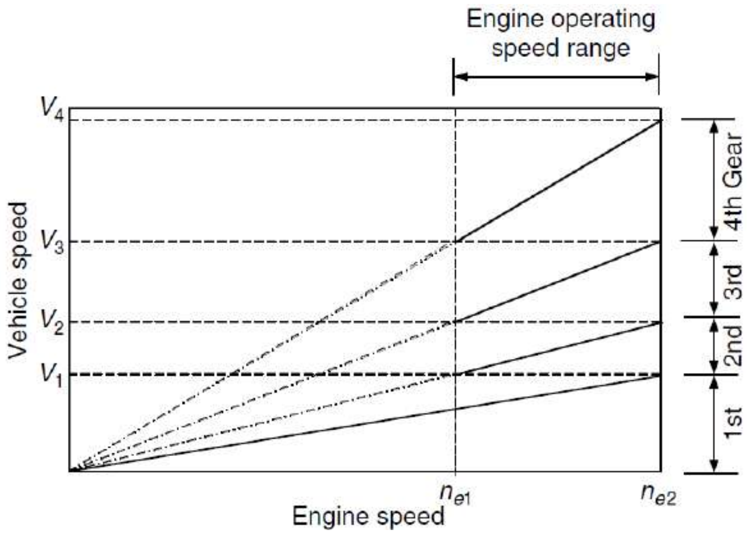


Fig 11. Demonstration of vehicle speed range and engine speed range for each gear

Transmission Characteristics: Manual Gear Transmission

- The tractive effort of a gasoline engine vehicle with four gear transmission and that of an electric vehicle with single-gear transmission.
- It is clear that electric machines with favorable torque–speed characteristics can satisfy tractive effort with simple single-gear transmission.

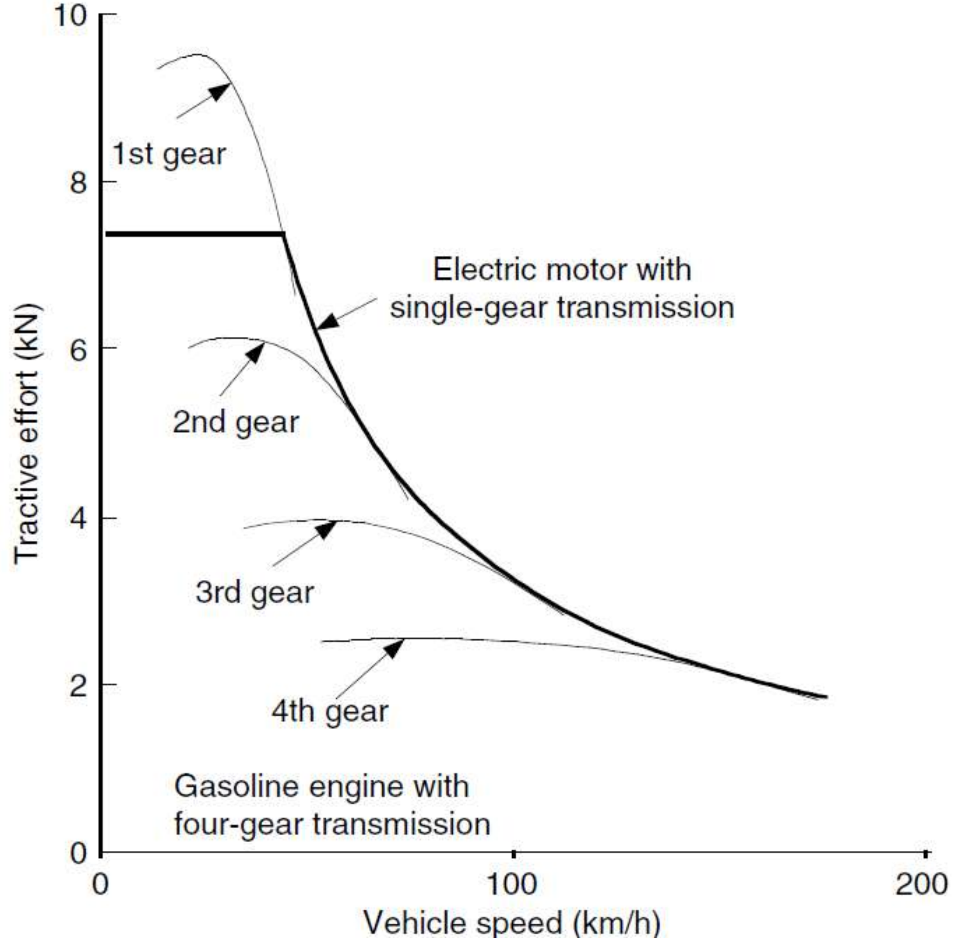
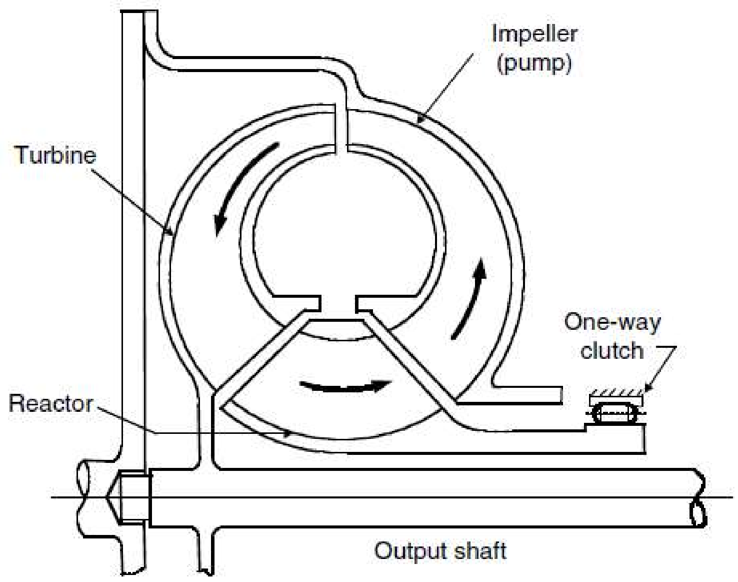


FIG 12: Tractive efforts of a gasoline engine vehicle with four-gear transmission and an electric vehicle with single-gear transmission

Transmission Characteristics: Hydrodynamic Transmission

- Hydrodynamic transmissions use fluid to transmit power in the form of torque and speed and are widely used in passenger cars.
- They consist of a torque converter and an automatic gearbox.
- The torque converter consists of at least three rotary elements known as the impeller (pump), the turbine, and the reactor, as shown in Fig13.
- The impeller is connected to the engine shaft and the turbine is connected to the output shaft of the converter, which in turn is coupled to the input shaft of the multispeed gearbox.
- The reactor is coupled to external housing to provide a reaction on the fluid circulating in the converter. The function of the reactor is to enable the turbine to develop an output torque higher than the input torque of the converter, thus producing torque multiplication.
- The reactor is usually mounted on a free wheel (oneway clutch) so that when the starting period has been completed and the turbine speed is approaching that of the pump, the reactor is in free rotation. At this point, the converter operates as a fluid coupled with a ratio of output torque to input torque that is equal to 1.0.



Schematic view of a torque converter

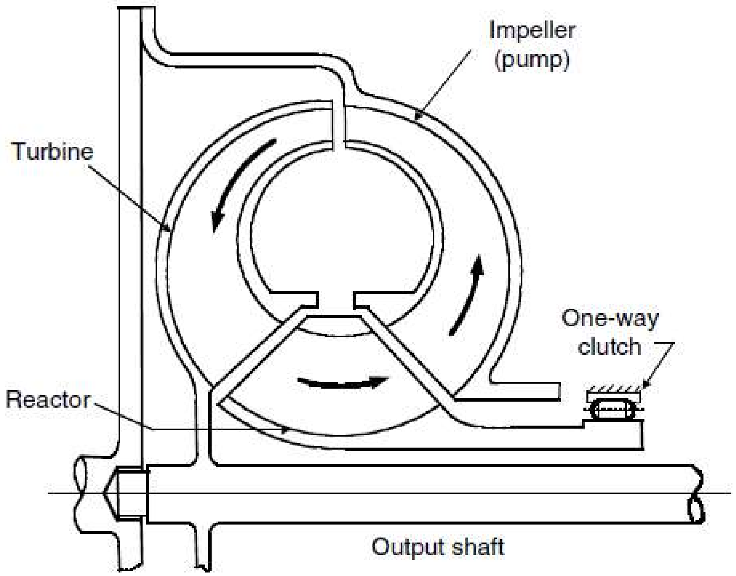
Transmission Characteristics: Hydrodynamic Transmission

Advantages

- When properly matched, the engine will not stall.
- It provides flexible coupling between the engine and the driven wheels.
- Together with a suitably selected multispeed gearbox, it provides torque–speed characteristics that approach the ideal.

Disadvantages:

- Low efficiency in a stop–go driving pattern and its complex construction.



Schematic view of a torque converter

Transmission Characteristics: Hydrodynamic Transmission

The performance characteristics of a torque converter are described in terms of the following four parameters

1. Speed Ratio $C_{sr} = \frac{Output\_Speed}{Input\_Speed}$ (This is reciprocal of the gear ratio)

2. Torque Ratio $C_{tr} = \frac{Output\_torque}{Input\_torque}$

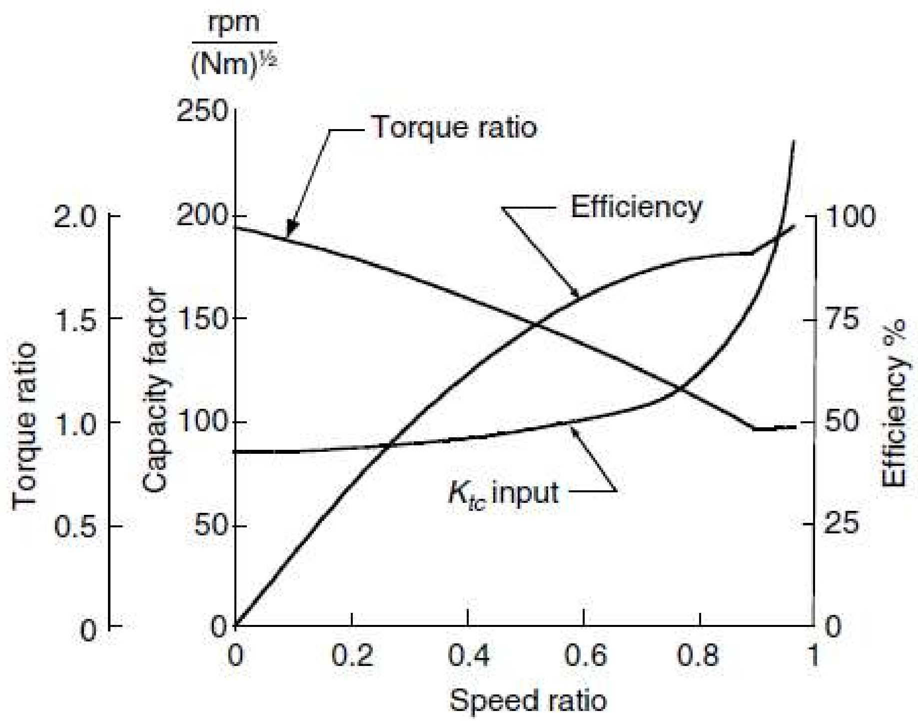
3. Efficiency = $\eta_{sr} = C_{sr}C_{tr} = \frac{Output\_Speed}{Input\_Speed} \text{ X } \frac{Output\_torque}{Input\_torque}$

4. Capacity factor (Size factor) $K_c = \frac{Speed}{\sqrt{torque}}$

- The capacity factor, *Kc,* is an indicator of the ability of the converter to absorb or transmit torque, which is proportional to the square of the rotary speed.

Transmission Characteristics: Hydrodynamic Transmission

- The torque ratio has the maximum value at stall condition, where the output speed is zero. The torque ratio decreases as the speed ratio increases (gear ratio decreases) and the converter eventually acts as a hydraulic coupling with a torque ratio of 1.0.
- At this point, a small difference between the input and output speed exists because of the slip between the impeller (pump) and the turbine.
- The efficiency of the torque converter is zero at stall condition and increases with increasing speed ratio (decrease in the gear ratio). It reaches the maximum when the converter acts as a fluid coupling (torque ratio equal to 1.0).
- To determine the actual operating condition of the torque converter, the engine operating point has to be specified because the engine drives the torque converter.
- Engine Capacity factor $K_e = \frac{n_e}{\sqrt{T_e}}$ Where n_e and T_e are engine speed and torque respectively.

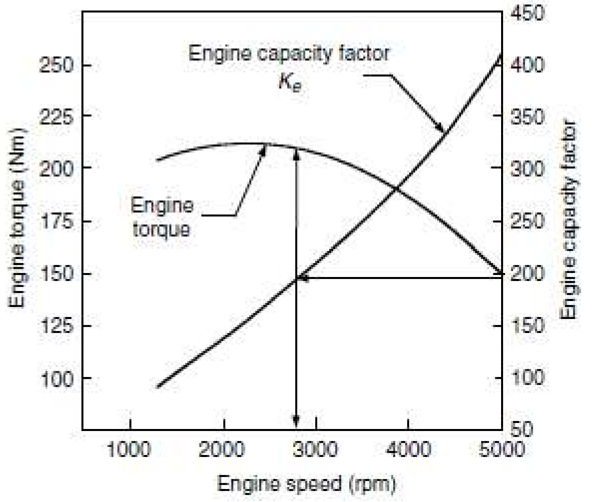


Performance characteristics of a torque converter

Transmission Characteristics: Hydrodynamic Transmission

The engine shaft is usually connected to the input shaft of the torque converter so K_e = K_c

If engine operating point is known, the engine capacity factor can be determined.
Since K_e = K_c, the input capacity factor of the torque converter corresponds to the specific engine operating point.
Output torque and output speed of the converter can be given by
$T_{tc} = T_e C_{tr}$ and
$n_{tc} = T_e C_{sr}$



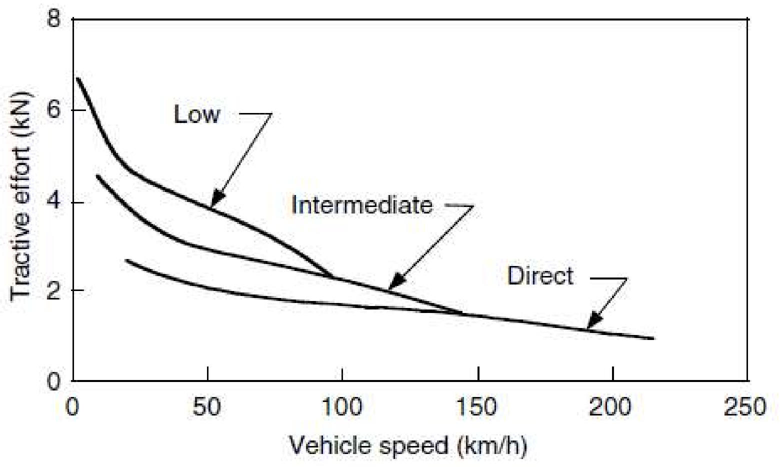
Capacity factor of a typical engine

Transmission Characteristics: Hydrodynamic Transmission

- Since the torque converter has a limited torque ratio range (usually less than 2), a multispeed gearbox is usually connected to it. The gearbox comprises several planetary gear sets and is automatically shifted.

So, $F_t = \frac{T_e C_{tr} i_g i_o \eta_t}{r}$

Speed $V = \frac{\pi n_e C_{sr} r}{30 i_g i_0}$ (m/s)



Tractive effort–speed characteristics of a passenger car with automatic transmission

III Year B. Tech. EEE II-Semester

Electric & Hybrid Vehicles
Course Code: PE116CW 3
(Professional Elective-II)

Prerequisites: Electrical Machines,
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Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
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Unit1:
Introduction to Hybrid Electric vehicles

Introduction:

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  - **Social and environmental importance of Hybrid and Electric vehicles**
- Vehicle Fundamentals:
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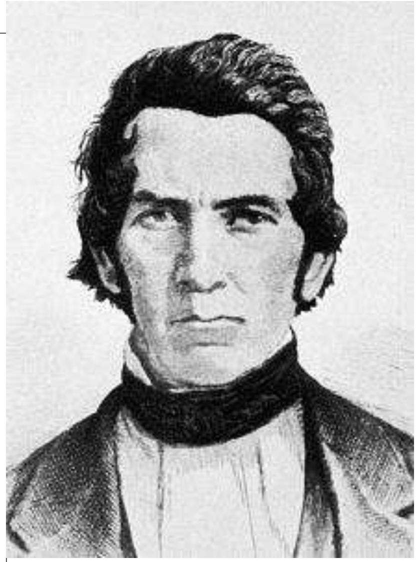
History of Electric vehicles

- https://interestingengineering.com/a-brief-history-and-evolution-of-electric-cars

Thomas Davenport (9 July 1802 – 6 July 1851)



- He was a blacksmith in Vermont Constructed DC Electric Motor in 1834.
- As early as 1834, he developed a battery-powered electric motor.
- He used it to operate a small model car on a short section of track, paving the way for the later electrification of streetcars.[2]
- Davenport's 1833 visit to the Penfield and Taft iron works at Crown Point, New York, where an electromagnet was operating, based on the design of Joseph Henry, was an impetus for his electromagnetic undertakings.
- Davenport bought an electromagnet from the Crown Point factory and took it apart to see how it worked. Then he forged a better iron core and redid the wiring, using silk from his wife's wedding gown.
- Received American patent on Elec Machine along with his wife Emily and colleague Orange Smalley,
- He used his electric motor in 1840 to print *The Electro-Magnetic and Mechanics Intelligencer* - the first newspaper printed using electricity.

Reference: https://en.wikipedia.org/wiki/Thomas_Davenport_(inventor)

Robert Davidson (inventor)

Scotland

- The first electric car is reported to have been developed in Scotland in 1839
- **Robert Davidson** (1804–1894) was a Scottish inventor who built the first known electric locomotive in 1837. He was a lifelong resident of Aberdeen, northeast Scotland, where he was a prosperous chemist and dyer, amongst other ventures.
- Davidson was educated at Marischal College, where he studied second and third year classes of Marischal College from 1819-1821,[1] including lectures from Professor Patrick Copland. He got this education in return for being a lab assistant.
- In the 1820s he set up in business close to the Aberdeen-Inver Davidson made a model electric locomotive in 1837. His *Galvani* of 1842 was a four-wheeled machine, powered by zinc-acid batteries. It was tested on the Edinburgh-Glasgow line in September 1842 and, although found capable of carrying itself at 4 mph, it did not haul any passengers or goods.[4]

Davidson's legacy[edit]

- He has been described as a forgotten hero and electrical visionary.[3] He could not interest the rail companies; the technology he employed was too expensive.[1]
- In 1840, the *Aberdeen Banner* had predicted that the type of machinery he was producing "will in no distant date supplant steam"; however, it was only when electric locomotives were introduced in the 1890s that the media came to recognize what he had done. He was described as the "oldest living electrician" and *The Electrician* magazine reported " Robert Davidson was undoubtedly the first to demonstrate the possibility of electrical traction in a practical way".[3]
- A working model of his electrical motor can be seen at the Grampian Transport Museum.

Reference: https://en.wikipedia.org/wiki/Robert_Davidson_(inventor)

Electric locomotives

- In 1834, Vermont blacksmith Thomas Davenport built a similar contraption which operated on a short, circular, electrified track. The first known electric locomotive was built in 1837, in Scotland by chemist Robert Davidson of Aberdeen. It was powered by galvanic cells (batteries). Davidson later built a larger locomotive named *Galvani*, exhibited at the Royal Scottish Society of Arts Exhibition in 1841.
- The 7,100-kilogram (7-long-ton) vehicle had two direct-drive reluctance motors, with fixed electromagnets acting on iron bars attached to a wooden cylinder on each axle, and simple commutators. It hauled a load of 6,100 kilograms (6 long tons) at 6.4 kilometers per hour (4 mph) for a distance of 2.4 km (1.5 miles).
- It was tested on the Edinburgh and Glasgow Railway in September of the following year, but the limited power from batteries prevented its general use. It was destroyed by railway workers, who saw it as a threat to their security of employment.
- A patent for the use of rails as conductors of electric current was granted in England in 1840, and similar patents were issued to Lilley and Colten in the United States in 1847. The first battery rail car was used in 1887 on the Royal Bavarian State Railways.

Reference: https://en.wikipedia.org/wiki/History_of_the_electric_vehicle

Beginning – 1801–1850

- The earliest electric vehicles were invented in Scotland and the USA.
- 1832–39 – Robert Anderson of Scotland built the first prototype electric carriage.
- 1834 – Thomas Davenport of the USA invented the first direct current electrical motor in a car that operates on a circular electrified track.

First Age – 1851–1900

- Electric vehicles enter the market and start to find broad appeal.
- 1888 German engineer Andreas Flocken built the first four-wheeled electric car.
- 1897 – The first commercial EVs entered the New York City taxi fleet. The Pope Manufacturing Company became the first large-scale EV manufacturer in the USA.
- 1899 The ‘La Jamais Contente’, built in France, became the first electric vehicle to travel over 100 km/h.
- 1900 Electricity-powered cars were the best selling road vehicle in the USA with about 28% of the market.

Boom and Bust – 1901–1950

- EVs reach historical peaks of production but are then displaced by petrol-engine cars.
- 1908 The petrol-powered Ford Model T was introduced to the market.
- 1909 William Taft was the first US President to buy an automobile, a Baker Electric.
- 1912 The electric starter motor was invented by Charles Kettering. This made it easier to drive petrol cars because hand cranking was not now necessary.
- The global stock of EVs reached around 30,000 by 1930
- By 1935, the number of EVs dropped almost to zero and ICE vehicles dominated because of cheap petrol.
- 1947 Oil rationing in Japan led carmaker Tama to release a 4.5 hp electric car. It used a 40V lead-acid battery.

Second Age – 1951–2000

- High oil prices and pollution created a new interest in electric vehicles.
- 1966 US Congress introduced legislation recommending EVs as a way of reducing air pollution.
- 1973 The OPEC oil embargo caused high oil prices, long delays at fuel stations, and therefore renewed interest in EVs.
- 1976 The French government launched the ‘PREDIT’, which was a programme accelerating EV research and development.
- 1996 To comply with California’s Zero Emission Vehicle (ZEV) requirements of 1990, GM produced the EV1 electric car.
- 1997 In Japan, Toyota began sales of the Prius, the world’s first commercial hybrid car. Eighteen thousand were sold in the first year.

Third Age – 2001–present

- Public and private sectors now commit to vehicle electrification.
- 2008 Oil prices reached record highs.
  2010 The Nissan LEAF was launched.
- 2011 The world's largest electric car sharing service, Autolib, was launched in Paris with a targeted stock of 3,000 vehicles.
- 2011 The global stock of EVs reached around 50,000. The French government fleet consortium committed to purchase 50,000 EVs over four years.
- Nissan LEAF won the European Car of the Year award.
- 2012 The Chevrolet Volt PHEV outsold half the car models on the US market. The global stock of EVs reached around 180,000.
- 2014 Tesla Model S, Euro NCAP 5-star safety rating, autopilot-equipped, available all-wheel drive dual motor with 0–60 mph in as little as 2.8 seconds and a range of up to 330 miles.
- 2015 Car manufacturers were caught cheating emission regulations making EVs more prominent in people's minds as perhaps the best way to reduce consumption and emissions.4 The global stock of EVs reached around 700,000 and continues to grow (22,000 in the UK and 275,000 in the USA).

EV — ?

ICE → EV

- → fuel cost
- → Pollution.
- → Efficiency
- → operating cost
- → Energy diversification

Challenges

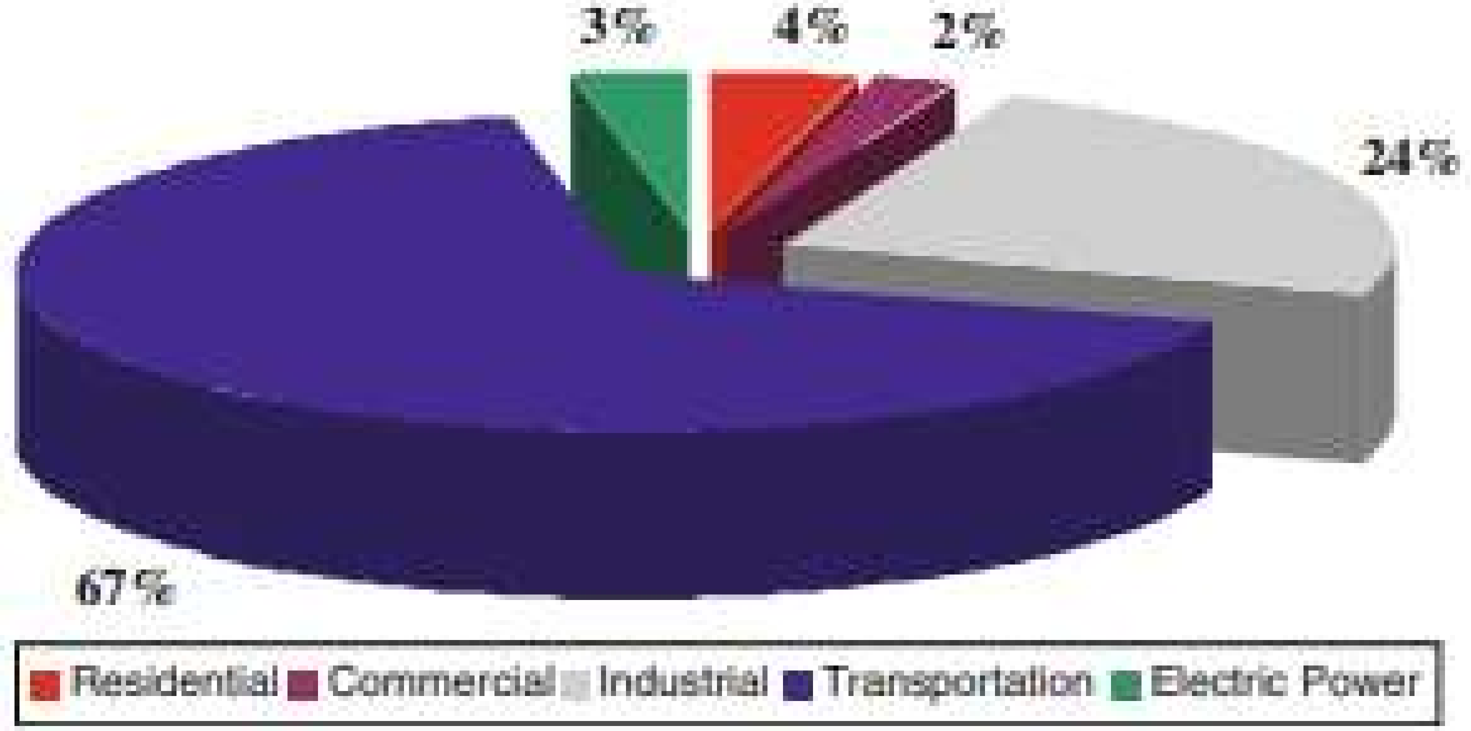
- → Initial cost high
- → Charging stations are not adequate
- → limited driving range
- → Technically trained people are less.

ICE

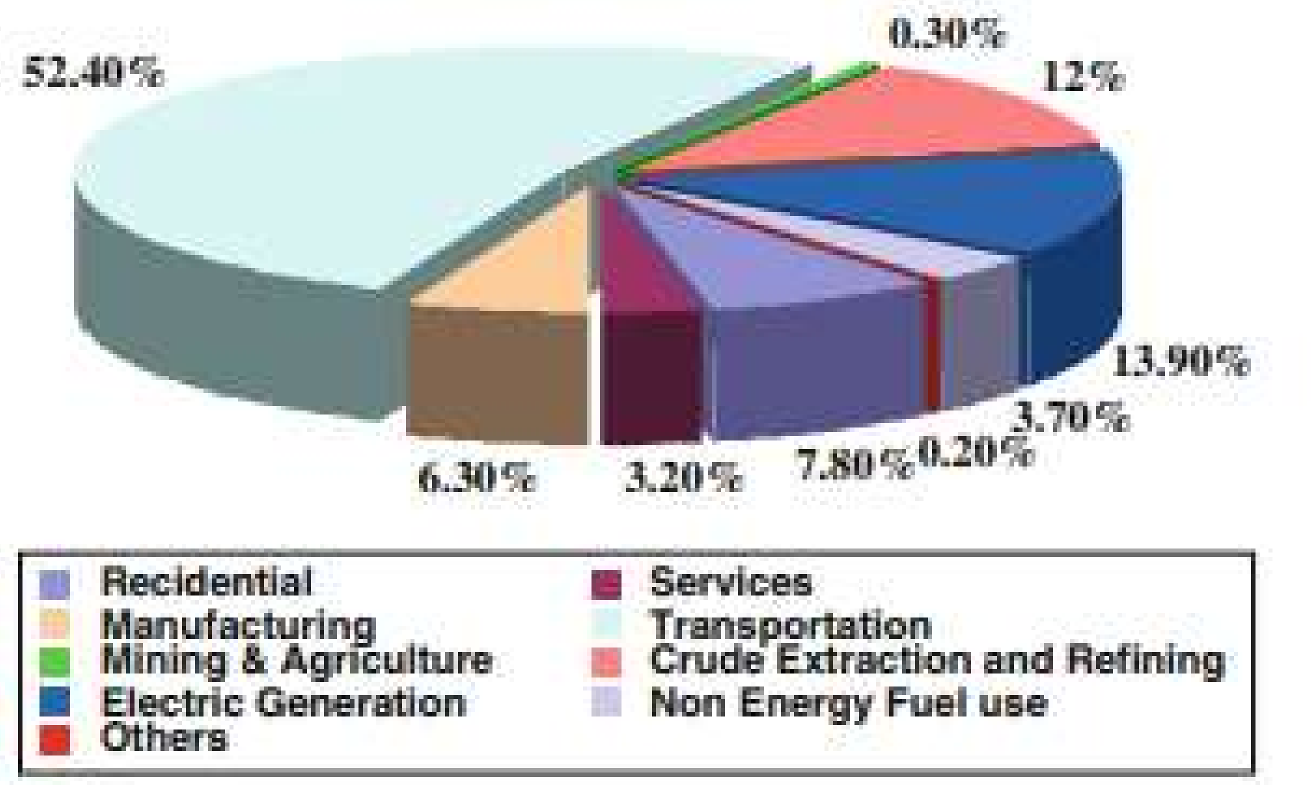
Engine
pet. tank
differential.
Transmission
Gear
clutch
brakes

Battery
Electric motor.
VCU
~~CEPS~~

Breakdown of oil usage by sector, 2006



Carbon dioxide emissions, 2006

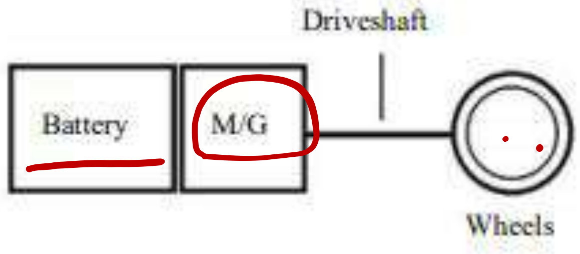


Components of a Hybrid Vehicle

Internal combustion
ICE → Engine

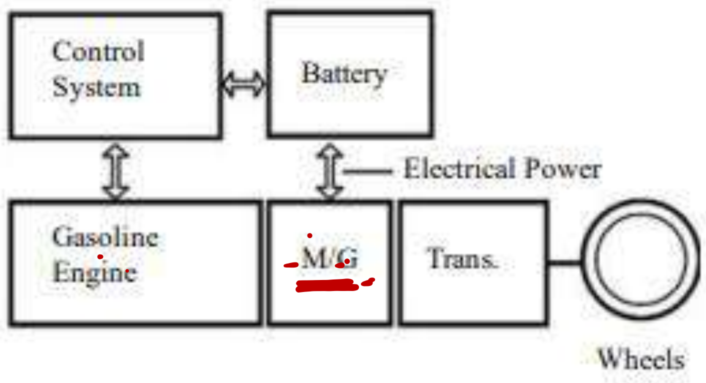
Gasoline
→ petrol
→ Diesel
→ CNG

Pure Electrical



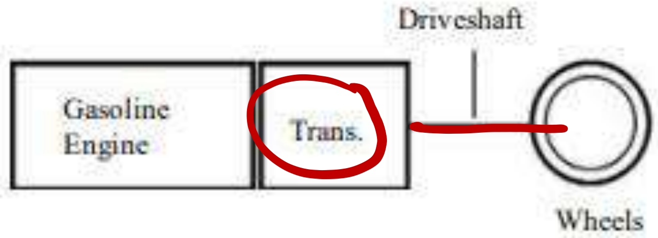
Hybrid

ICE + EV

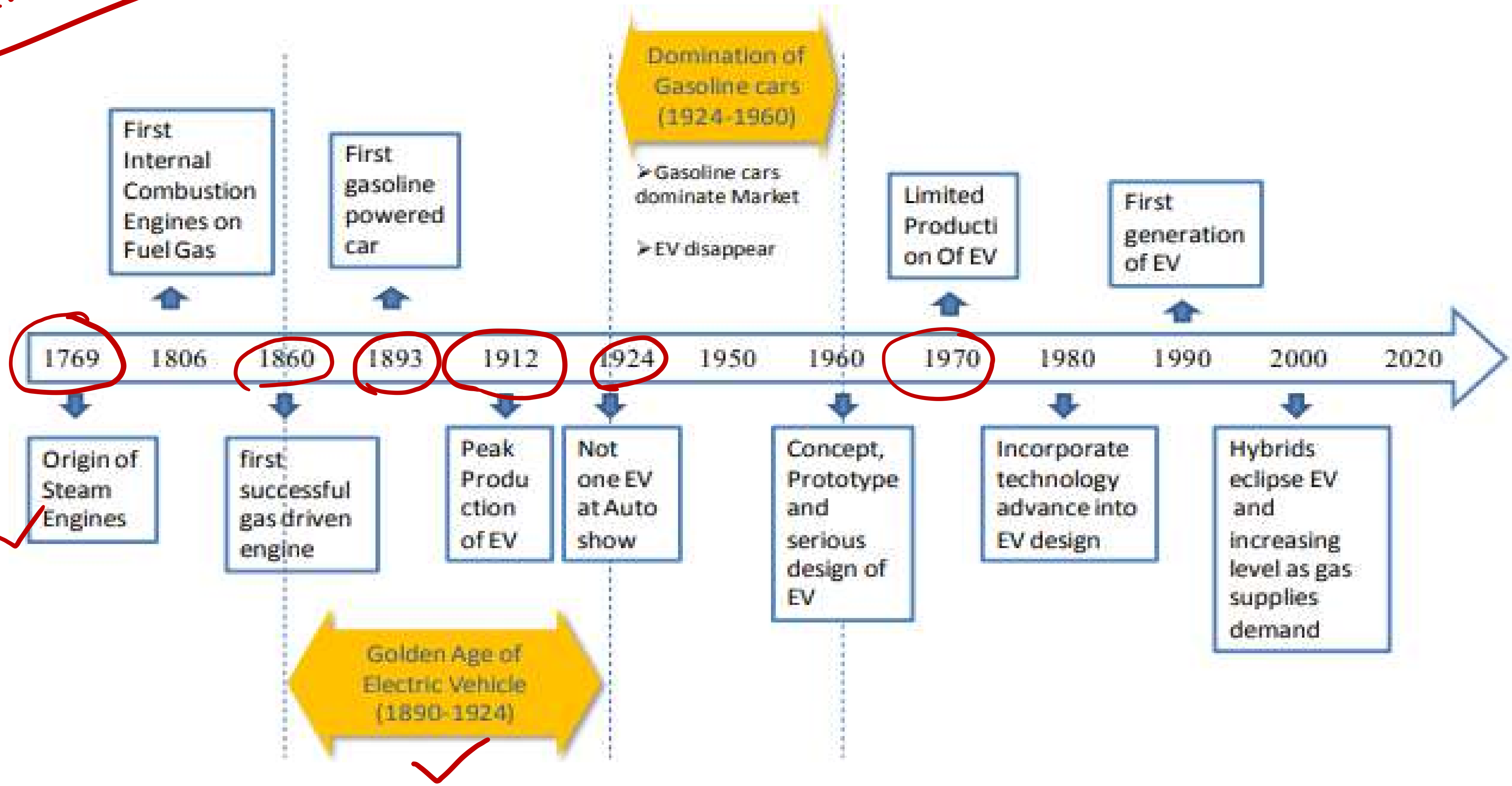


Trans
Transmission
Gear.

Pure Gasoline



Historical development of automobile and development



1769 - 1888

1769	**The first steam-powered vehicle** was designed by **Nicolas-Joseph Cugnot** and constructed by **M. Brezin** that could attain speeds of up to 6 km/hour. These early steam-powered vehicles were so heavy that they were only practical on a perfectly flat surface as strong as iron.
1807	The next step towards the development of the car was the invention of the internal combustion engine. **Francois Isaac de Rivaz designed the first internal combustion engine** in, using **a mixture of hydrogen and oxygen to generate energy.**
1825	British inventor **Goldsworthy Gurney** built **a steam car** that successfully completed an **85 mile** round-trip journey in ten hours time.
1839	***Robert Anderson of Aberdeen, Scotland built the first electric vehicle.***
1860	In, **Jean Joseph Etienne Lenoir,** a Frenchman, built the **first** successful **two-stroke gas driven engine**.
1886	Historical records indicate that an **electric-powered taxicab**, using a **battery with 28 cells** and a **small electric motor**, **was introduced in England**.
1888	**Immisch & Company built a four-passenger carriage,** powered by a **one-horsepower motor** and **24-cell battery**, for the Sultan of the Ottoman Empire. In the same year, Magnus Volk in Brighton, England made a three-wheeled electric car.

1890 – 1910 (Period of significant improvements in battery technology) Invention Of hybrid vehicle	
1890	Jacob Lohner, a coach builder in Vienna, Austria, foresaw the need for an electric vehicle that would be less noisy than the new gas-powered cars. He commissioned a design for an electric vehicle from Austro-Hungarian engineer Ferdinand Porsche, who had recently graduated from the Vienna Technical College. Porsche's first version of the electric car used a pair of electric motors mounted in the front wheel hubs of a conventional car. The car could travel up to 38 miles. To extend the vehicle's range, Porsche added a gasoline engine that could recharge the batteries, thus giving birth to the first hybrid, the Lohner Porsche Elektromobil.
Early Hybrid Vehicles **1900**	Porsche showed his hybrid car at the Paris Exposition of 1900. A gasoline engine was used to power a generator which, in turn, drove a small series of motors. The electric engine was used to give the car a little bit of extra power. This method of series hybrid engine is still in use today, although obviously with further scope of performance improvement and greater fuel savings
1915	Woods Motor Vehicle manufacturers created the Dual Power hybrid vehicle, second hybrid car in market. Rather than combining the two power sources to give a single output of power, the Dual Power used an electric battery motor to power the engine at low speeds (below 25km/h) and used the gasoline engine to carry the vehicle from these low speeds up to its 55km/h maximum speed. While Porsche had invented the series hybrid, Woods invented the parallel hybrid.
1918	The Woods Dual Power was the first hybrid to go into mass production. In all, some 600 models were built by. However, the evolution of the internal combustion engine left electric power a marginal technology

1960	***Victor Wouk*** **worked in helping create numerous hybrid designs earned him the nickname of the "Godfather of the Hybrid".** **In 1976 he even converted a Buick Skylark from gasoline to hybrid.**
1978	Modern hybrid cars rely on the regenerative braking system. When a standard combustion engine car brakes, a lot of power is lost because it dissipates into the atmosphere as heat. Regenerative braking means that the electric motor is used for slowing the car and it essentially collects this power and uses it to help recharge the electric batteries within the car. This development alone is believed to have progressed hybrid vehicle manufacture significantly. **The Regenerative Braking System, was first designed and developed in 1978 by David Arthurs.** Using standard car components he converted an Opel GT to offer 75 miles to the gallon and many home conversions are done using the plans for this system that are still widely available on the Internet.

Modern Period of Hybrid History The history of hybrid cars is much longer and more involved than many first imagine. It is, however, in the last ten years or so that we, as consumers, have begun to pay more attention to the hybrid vehicle as a viable alternative to ICE driven cars. Whether looking for a way to save money on spiraling gas costs or in an attempt to help reduce the negative effects on the environment we are buying hybrid cars much more frequently. much more frequently.	
1990	Automakers took a renewed interest in the hybrid, seeking a solution to dwindling energy supplies and environmental concerns and created modern history of hybrid car
1993	In USA, Bill Clinton's administration recognized the urgency for the mass production of cars powered by means other than gasoline. Numerous government agencies, as well as Chrysler, Ford, GM, and USCAR combined forces in the PNGV (Partnership for a New Generation of Vehicles), to create cars using alternative power sources, including the development and improvement of hybrid electric vehicles.
1997	The Audi Duo was the first European hybrid car put into mass production and hybrid production and consumer take up has continued to go from strength to strength over the decades.
2000	Toyota Prius and Honda Insight became the first mass market hybrids to go on sale in the United States, with dozens of models following in the next decade. The Honda Insight and Toyota Prius were two of the first mainstream Hybrid Electric Vehicles and both models remain a popular line.
2005	A hybrid Ford Escape, the SUV, was released in 2005. Toyota and Ford essentially swapped patents with one another, Ford gaining a number of Toyota patents relating to hybrid technology and Toyota, in return, gaining access to Diesel engine patents from Ford

- **Present of Hybrid Electric vehicle** Toyota is the most prominent of all manufacturers when it comes to hybrid cars.
- As well as the specialist hybrid range they have produced hybrid versions of many of their existing model lines, including several Lexus (now owned and manufactured by Toyota) vehicles.
- As well as cars and SUVs, there are a select number of hybrid motorcycles, pickups, vans, and other road going vehicles available to the consumer and the list is continually increasing.

ICE + EV

- **Future of Hybrid electrical vehicle** Since petroleum is limited and will someday run out of supply.
- In the arbitrary year 2037, an estimated one billion petroleum-fueled vehicles will be on the world's roads.
- gasoline will become prohibitively expensive. The world need to have solutions for the "400 million otherwise useless cars".
- So year 2037 "gasoline runs out year" means, petroleum will no longer be used for personal mobility. A market may develop for solar-powered EVs of the size of a scooter or golf cart.
- Since hybrid technology applies to heavy vehicles, hybrid buses and hybrid trains will be more significant.

HEV = ICE + EV

Hybrid energy sourced vehicle

Batt + flywheel, Batt + solar

Social Economic and Environmental Impact of Electric Hybrid Vehicle

- Usage of the Fossil fuels in automobiles emit CO_2 in great extent.
- Countries around the world are working to drastically reduce CO_2 emissions as well as other harmful environmental pollutants.
- According to various reports, cars and trucks are responsible for almost 25% of CO_2 emission and other major transportation methods account for another 12%.
- One alternative to standard ICE vehicles is Hybrid Cars.
- Cost effectiveness is also vehicle combines any type of two power (energy) sources. Possible combinatimportant factor in contributing to the development of an environment friendly transportation sector.
- **Hybrid Vehicle:** A hybrid ons include diesel/electric, gasoline/fly wheel, and fuel cell (FC)/battery.
- In the majority of modern hybrids, cars are powered by a combination of traditional gasoline power and the addition of an electric motor.

Social Economic and Environmental Impact of Electric Hybrid Vehicle

- At present, all vehicles rely on the combustion of hydrocarbon fuels to derive the energy necessary for their propulsion. Combustion is a reaction between the fuel and the air that releases heat and combustion products
- the combustion of hydrocarbon fuel in combustion engines is never ideal. Besides carbon dioxide and water, the combustion products contain a certain amount of nitrogen oxides (NOx), carbon monoxides (CO), and unburned hydrocarbons (HC), all of which are toxic to human health

THE ELECTRIC CAR
PAST AND FUTURE

1832
First crude EVs developed

1901
Thomas Edison works to develop better EV batteries

World's first hybrid electric car invented

1900-1912
EVs reach their heyday

1920-1935
Cheap Texas crude oil fuels decline in electric vehicles

1971
Electric lunar rover is first manned vehicle to drive on moon

1973
General Motors unveils prototype for urban EV

1974-1977
U.S. carmaker Sebring-Vanguard produces more than 2,000 CitiCar EVs, which have range of 80-97km

1990-1992
New U.S. environmental regulations renew interest in EVs

1996
GM releases EV1, first mass-produced EV by major automaker

1997
Toyota introduces Prius, world's first mass-produced hybrid

2008
Tesla launches commercial production of Roadster EV

China's BYD Auto releases F3DM, world's first plug-in hybrid

2009-2013
U.S. government installs 18,000 residential, commercial, public chargers

2010
Nissan releases all-electric Leaf

2014
Tesla breaks ground on massive Gigafactory 1 battery plant in U.S. state of Nevada

2016
GM releases Chevy Bolt, its first electric car

Chinese Finance Minister Lou Jiwei says country will totally phase out subsidies for green energy vehicles by 2021

2017
MARCH
India's power minister suggests country aims for EV-only sales by 2030

JULY
France, U.K. say they will end sales of gasoline, diesel vehicles by 2040

OCTOBER
GM says it will launch at least 20 new electric, fuel-cell vehicles by 2023

2020
Tesla targets annual sales of 1 million cars

2025
VW targets annual sales of 2-3 million EVs by this year

BMW wants EVs to account for 15-25% of group sales by this year

2030
Up to 200 million EVs projected to be in circulation

2040
EVs projected to account for 32% of global auto sales

Prius photo by Reuters, others by Getty Images
Sources: International Energy Agency's Global EV Outlook 2017 report, U.S. Department of Energy

Comparison of conventional vehicle to EV

Conventional ICE Type Vehicle	Electric vehicle or Hybrid electric vehicle
• To start the engine and run the auxiliary items usage of battery is needed. • It must require cranking amperes to ignite the engine. • Normally low voltage is used and the battery is lead acid type, Flooded, Gel type batteries used. • Engine driven alternator keeps the battery charged.	• Battery is the energy source for propulsion. • Normally high capacity batteries and Lithium ion type batteries used. • Charging through power grid or engine takes place. • Batteries need to be handled with care.

III Year B. Tech. EEE II-Semester

Electric & Hybrid Vehicles

Course Code: PE116CW 3

(Professional Elective-II)

Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

Unit1:
Introduction to Hybrid Electric vehicles

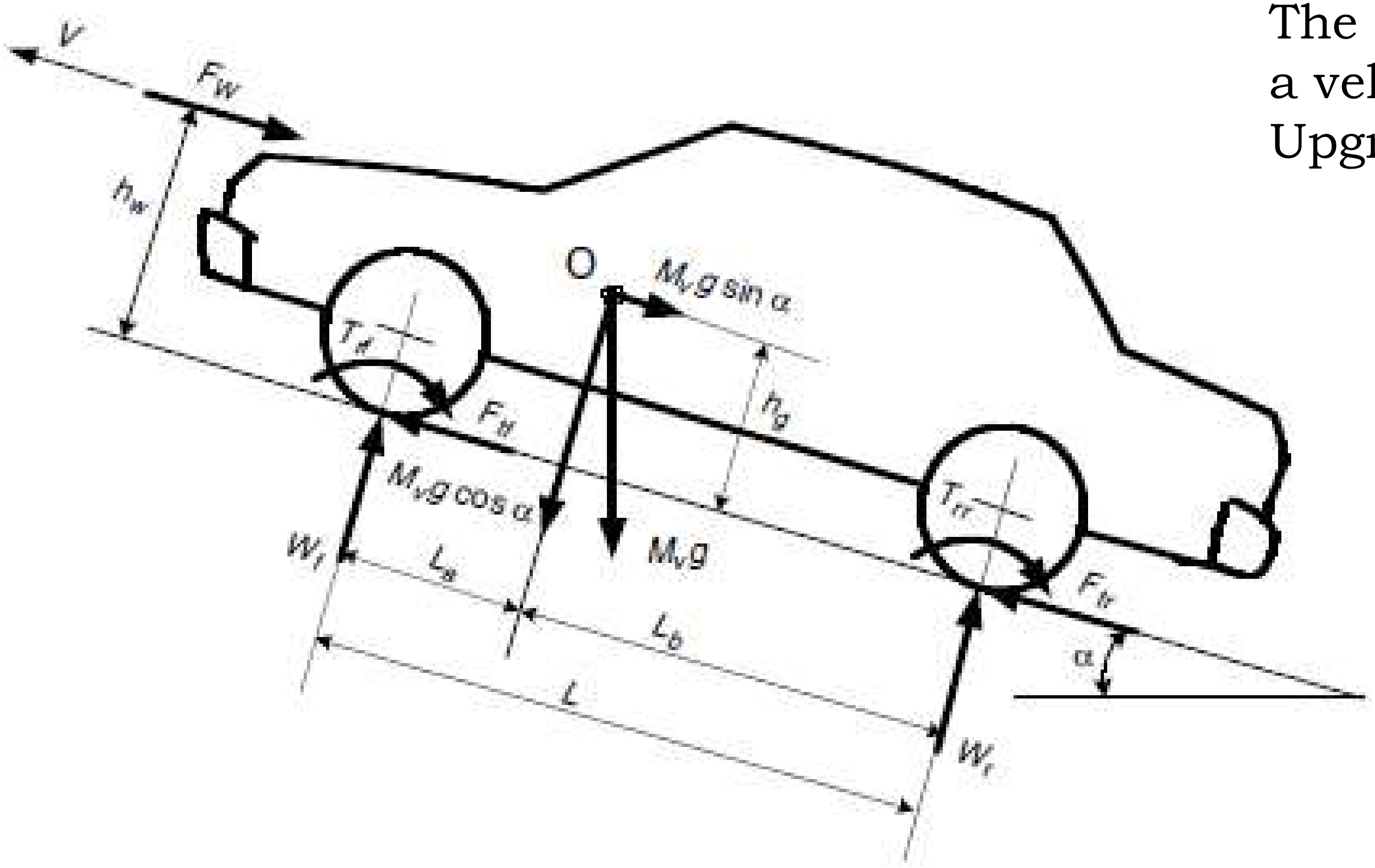
Introduction:

- Introduction to Hybrid Electric vehicles:
  - History of Hybrid Electric Vehicles
  - Social and environmental importance of Hybrid and Electric vehicles
- Vehicle Fundamentals:
  - **Vehicle Resistance**
  - **Dynamic Equation**
  - Tire-Ground Adhesion and Maximum Tractive effort
  - Power Train Tractive effort and Vehicle speed
  - Vehicle power Plant and Transmission Characteristics
  - Vehicle Performance
  - Operating Fuel Economy braking Performance

Vehicle Fundamentals

- Vehicle operation fundamentals mathematically describe vehicle behavior based on the general principles of mechanics.
- A vehicle, is a complex system with thousands of components.
- Vehicle is described both mechanically and mathematically.
- Vehicle performance speed, gradeability, acceleration, Fuel consumption, and braking performance are discussed as fundamentals here
- .

Forces acting on a vehicle



The figure shows the forces acting on a vehicle when the vehicle moving Upgrade with Tractive effort Ft:

The tractive effort, F_t, in the contact area between tires of the driven wheels and the road surface propels the vehicle forward.

It is produced by the power plant torque and is transferred through transmission and final drive to the drive wheels.

While the vehicle is moving, there is resistance that tries to stop its movement.

Vehicle resistance includes

- Rolling Resistance force
- Aerodynamic Force
- Uphill resistance

Acceleration equation

- Vehicle acceleration according to Newton's second law is
- $\frac{dV}{dt} = \frac{\sum F_t - \sum F_{tr}}{\delta M_v}$ --1
- The equation tells that the vehicle speed depends on the speed and acceleration depend on tractive effort, resistance and vehicle mass.
- Where V → Vehicle speed
- $\sum F_t$ → Total Tractive effort of the vehicle
- $\sum F_{tr}$ → Total resistance

- M_v → Total mass of the vehicle
- δ→ Mass factor (effect of rotating components in the power train)

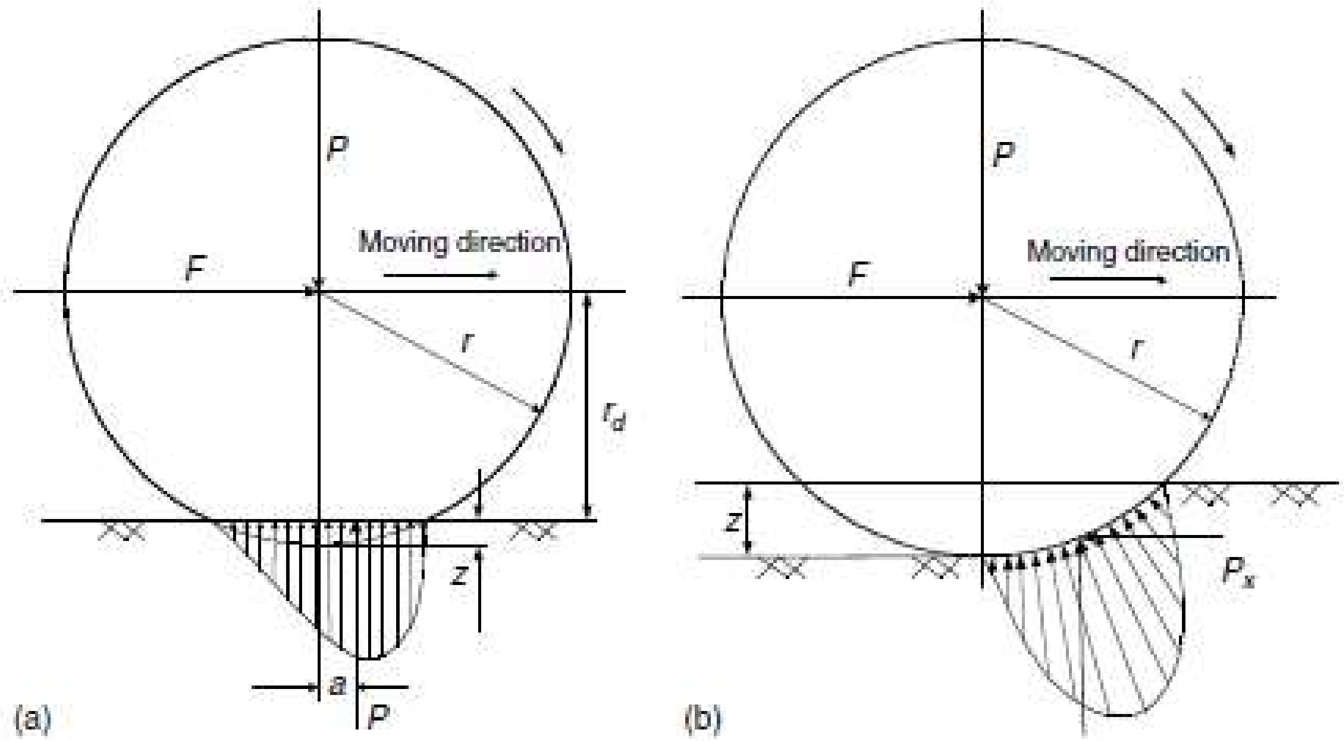
Vehicle Resistance (Rolling resistance)

- Rolling resistance appears near the tires of the vehicle.
- Trf → Torque due to front wheel
- Trr→ Torque due to rear wheel

Rolling resistance depends on the road surface, mass of the vehicle, radius of the wheel.

- The rolling resistance of tires on hard surfaces is primarily caused by hysteresis in the tire materials. This is due to the deflection of the carcass while the tire is rolling. The hysteresis causes an asymmetric distribution of ground reaction forces.

Rolling Resistance Force



Tire deflection and rolling resistance on a (a) hard and (b) soft road surface

The moment produced by the forward shift of the resultant ground reaction force is called the rolling resistant moment

$$T_r = Pa$$

Where P is the normal load acting on centre of the rolling wheel and a is the deflection of the wheel.

Force acting on the wheels

$$F_r = \frac{T_r}{r_d} = \frac{Pa}{r_d}$$

r_d is the effective radius of the tire

$f_r = \frac{a}{r_d}$ or $\mu_r = \frac{a}{r_d}$

Here f_r is the rolling resistance coefficient.

Equivalent rolling resistance force $F_r = Pf_r$

When the vehicle operates on slope road, normal load P is replaced by the perpendicular component of the road surface. So $F_r = Pf_r \cos\alpha$

Rolling Resistance Coefficients

The rolling resistance coefficient, f_r, is a function of the

- Tire material,
- Tire structure,
- tire temperature,
- tire inflation pressure,
- tread geometry,
- road roughness,
- road material,
- and the presence or absence of liquids on the road.

Conditions	Rolling resistance coefficient
Car tires on concrete or asphalt	0.013
Car tires on rolled gravel	0.02
Tar macadam	0.025
Unpaved road	0.05
Field	0.1–0.35
Truck tires on concrete or asphalt	0.006–0.01
Wheels on rail	0.001–0.002

The rolling resistance coefficient of passenger cars on concrete road may be calculated from the following equation:

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

V→ Vehicle speed in Km/h

f_o , f_s → Depends on inflation pressure of the tires

Most commonly it is considered as

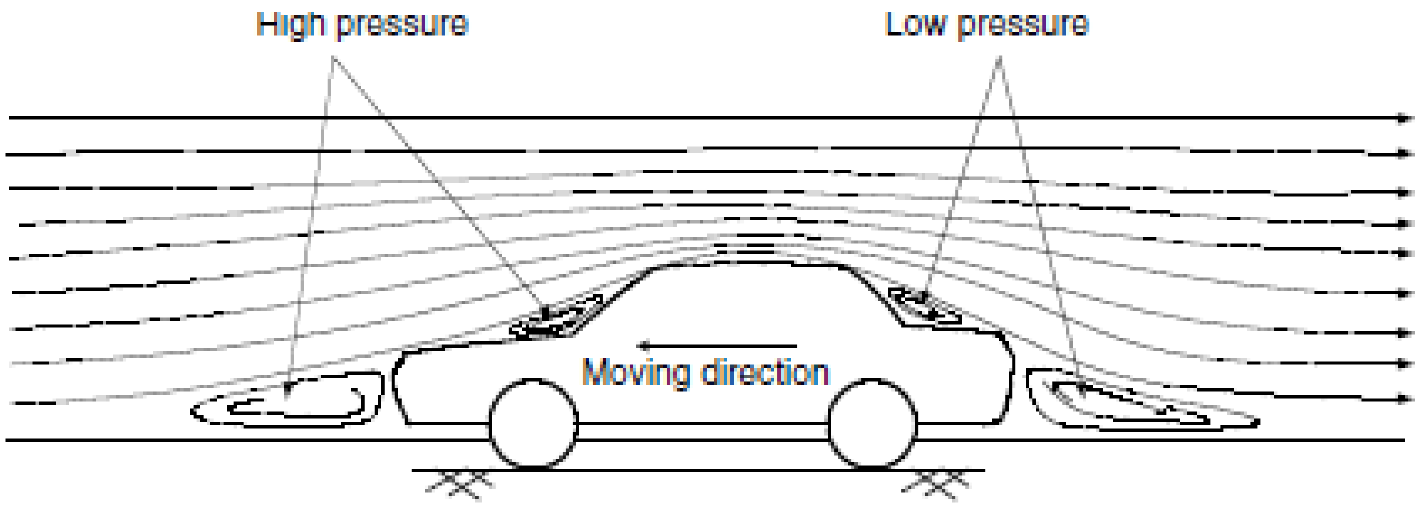
$$f_r = 0.01\left(1 + \frac{V}{100}\right)$$

Aerodynamic Drag

A vehicle traveling at a particular speed in air encounters a force resisting its motion. This force is referred to as aerodynamic drag. It mainly results from

- shape drag and
- skin friction.

Shape drag

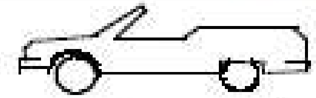
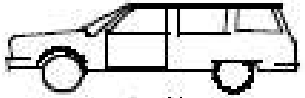
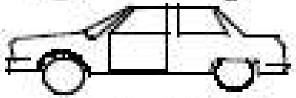
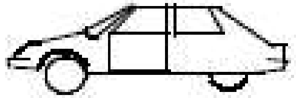
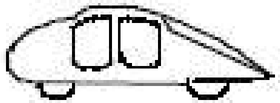
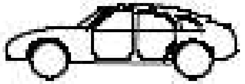
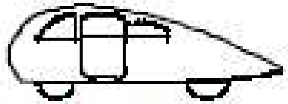


- The forward motion of the vehicle pushes the air in front of it. However, the air cannot instantaneously move out of the way and its pressure is thus increased, resulting in high air pressure.
- In addition, the air behind the vehicle cannot instantaneously fill the space left by the forward motion of the vehicle. This creates a zone of low air pressure.
- The motion has therefore created two zones of pressure that oppose the motion of a vehicle by pushing it forward (high pressure in front) and pulling it backward (low pressure in the back)
- The resulting force on the vehicle is the shape drag.

Skin friction

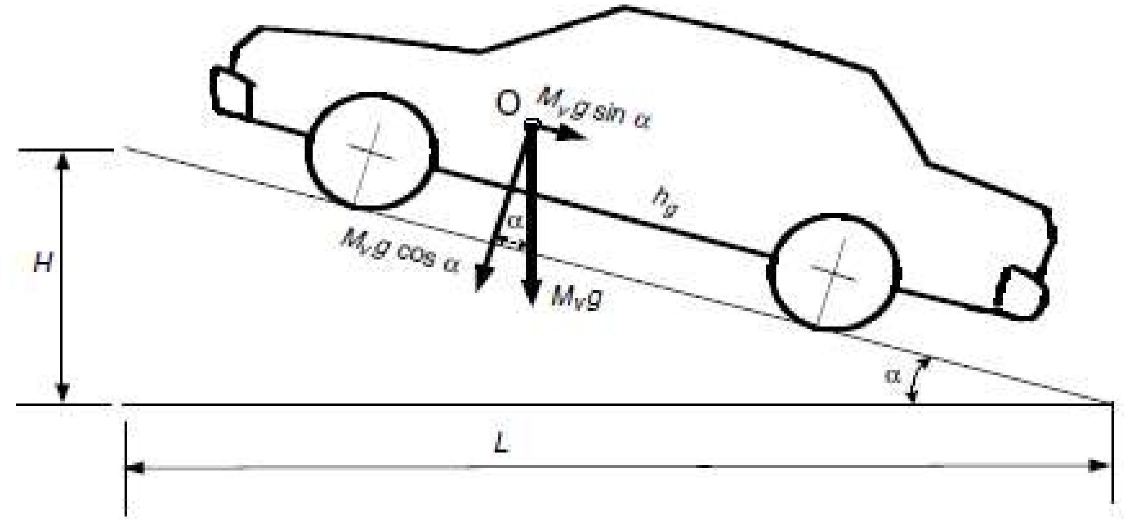
- Air close to the skin of the vehicle moves almost at the speed of the vehicle while air far from the vehicle remains still. In between, air molecules move at a wide range of speeds.
- The difference in speed between two air molecules produces a friction that results in the second component of aerodynamic drag.
- Aerodynamic drag is a function of vehicle speed V, vehicle frontal area Af, shape of the vehicle, and air density ρ.
- Aerodynamic drag is expressed as $F_w = \frac{1}{2} \rho A_f C_d (V + V_w)^2$
- C_d is the aerodynamic drag coefficient that characterizes the shape of the vehicle and V_w is the component of wind speed on the vehicle's moving direction, which has a positive sign when this component is opposite to the vehicle speed and a negative sign when it is in the same direction as vehicle speed.
- The aerodynamic drag coefficients for a few types of vehicle body shapes

<u>Indicative drag coefficients for different body shapes</u>

Vehicle Type	Coefficient of Aerodymanic Resistance
 Open convertible	0.5–0.7
 Van body	0.5–0.7
 Ponton body	0.4–0.55
 Wedge-shaped body; headlamps and bumpers are integrated into the body, covered underbody, optimized cooling air flow	0.3–0.4
 Headlamp and all wheels in body, covered underbody	0.2–0.25
 K-shaped (small breakway section)	0.23
 Optimum streamlined design	0.15–0.20
Trucks, road trains	0.8–1.5
Buses	0.6–0.7
Streamlined buses	0.3–0.4
Motorcycles	0.6–0.7

Grading Resistance

- When a vehicle goes up or down a slope, its weight produces a component, which is always directed to the downward direction, as shown in Figure.
- This component either opposes the forward motion (grade climbing) or helps the forward motion (grade descending). In vehicle performance analysis, only uphill operation is considered. This grading force is usually called grading resistance.



$F_g = M_v g sin\alpha$

To simplify the calculation, road angle α, is usually replaced with the grade value when road angle is small.

I $= \frac{H}{L} = tan\alpha \approx sin\alpha$

Note: Tire rolling resistance and gradient resistance together is called Road resistance

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

Road resistance can be simplified as

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

Dynamic Equation

- In the longitudinal direction, the major external forces acting on a two-axle vehicle, as shown in Figure 2.1, include the rolling resistance of front and rear tires *Frf* and *Frr*, which are represented by rolling resistance moment *Trf* and *Trr*, aerodynamic drag *Fw*, grading resistance *Fg* (*Mv g* sinα), and tractive effort of the front and rear tires, *Ftf* and *Ftr*. *Ftf* is zero for a rear-wheel-driven vehicle, whereas *Ftr* is zero for a front-wheel-driven vehicle.

$$M_v \frac{dV}{dt} = (F_{tf} + F_{tr}) - (F_{rf} + F_{rr} + F_w + F_g),$$

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  - Vehicle power Plant and Transmission Characteristics
  - **Vehicle Performance**
  - Operating Fuel Economy braking Performance

Vehicle Performance

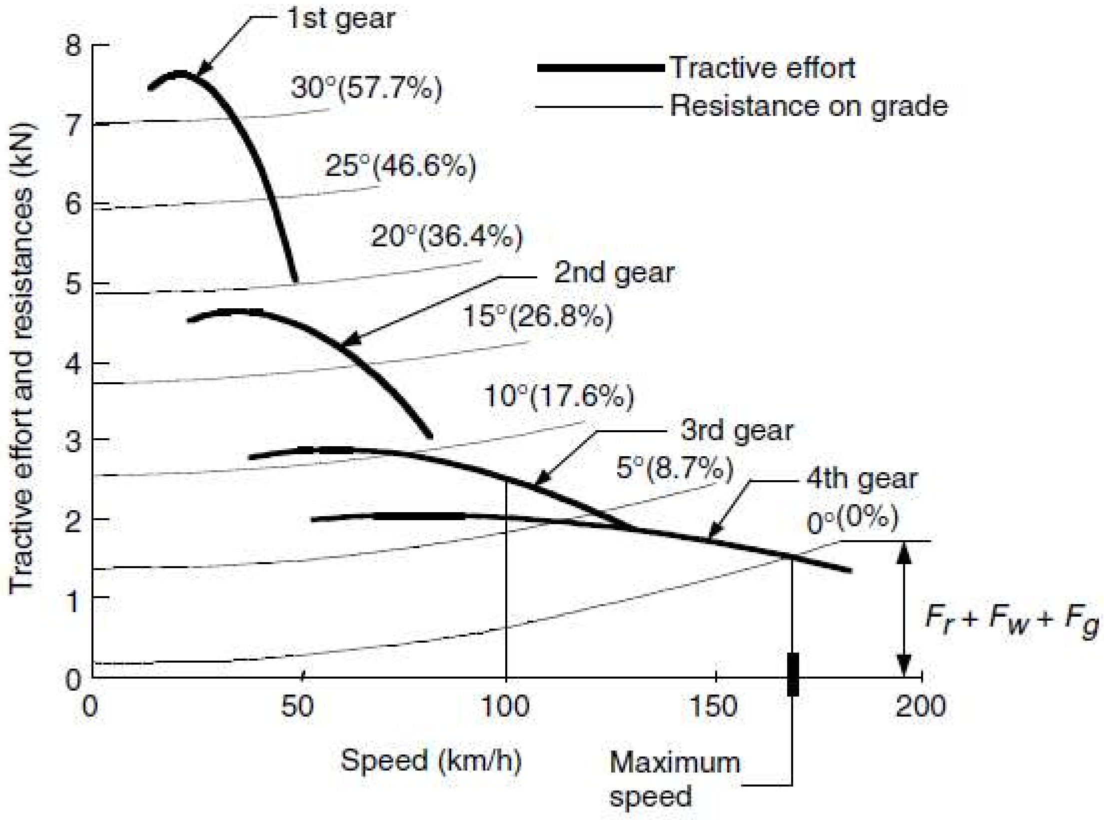
The performance of a vehicle is described by its

- Maximum cruising
- Speed
- Gradeability, and
- Acceleration.

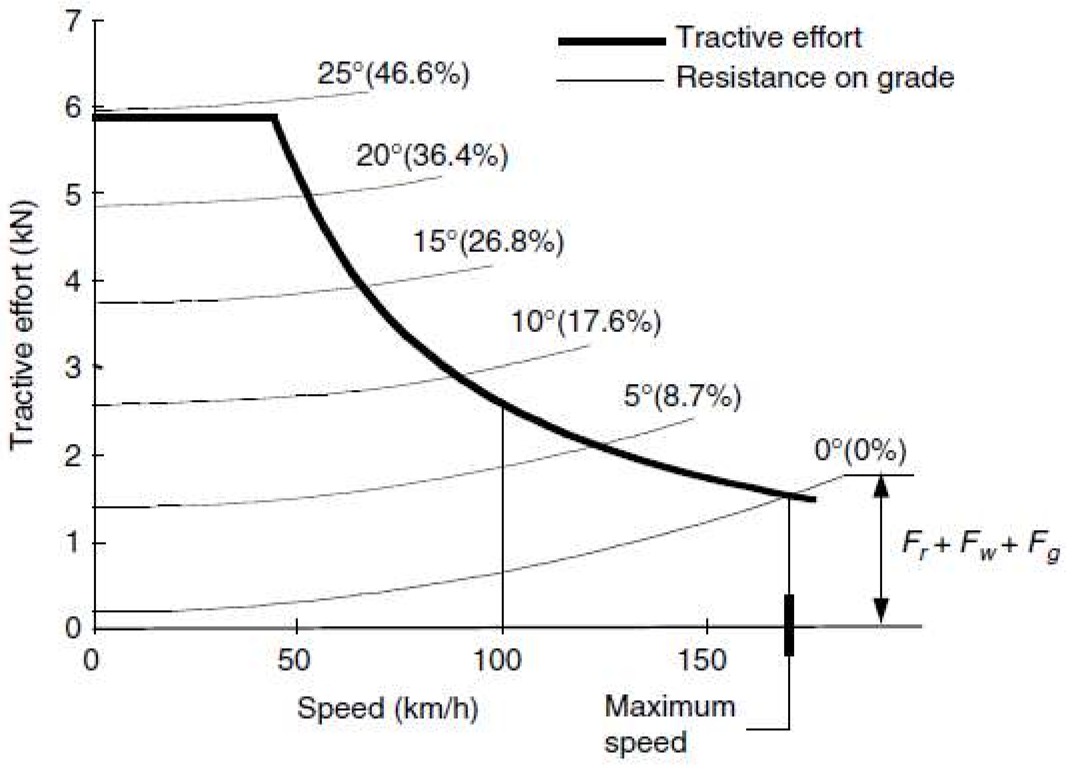
Vehicle performance prediction is based on the relationship between tractive effort and vehicle speed.

For On road vehicles it is assumed that the Max. Tractive effort (F_{tmax}) is limited by the Max Torque (T_{max}) of the power plant rather than road adhesive capability

Comparison of ICE and Electric vehicles transmission performance



Tractive effort of a gasoline engine-powered vehicle with multispeed transmission and its resistance



Tractive effort of an electric motor-powered vehicle with single-speed transmission and its resistance

Maximum speed of a vehicle

- The maximum speed of a vehicle is defined as the constant cruising speed that the vehicle can develop with full power plant load (full throttle of the engine or full power of the motor) on a flat road.
- The maximum speed of a vehicle is determined by the equilibrium between the tractive effort of the vehicle and the resistance or the maximum speed of the power plant and gear ratios of the transmission.
- The tractive effort and resistance equilibrium can be expressed as

$$\frac{T_p i_g i_o \eta_t}{r_d} = M_v g f_r \cos\alpha + \frac{1}{2}\rho_a C_D A_f V^2 \rightarrow 1$$

- The equation tells that vehicle reaches its max speed when the tractive effort equals the resistance.
- Intersection of the tractive effort curve and the resistance curve represents the max speed of the vehicle.

Maximum Speed of a Vehicle

In some vehicles there no interaction exists between the effort curve and the resistance curve, because of a large power plant or large gear ratio. In this case Max speed of the vehicle can be determined by the max speed of the power plant.

$$V_{max} = \frac{\pi n_{pmax} r_d}{30\, i_o i_{g\,min}} \text{ (m/s)} \rightarrow 2$$

Where n_{pmax} and $igmin$ are the max speed of the engine and the minimum gear ratio of the transmission respectively.

Gradeability

- Gradeability is usually defined as the grade (or grade angle) that the vehicle can overcome at a certain constant speed, for instance, the grade at a speed of 100 km/h (60 mph).
- For heavy commercial vehicles or off-road vehicles, the gradeability is usually defined as the maximum grade or grade angle in the whole speed range.

Gradeability

- When the vehicle drives on a road with relative small grade and constant speed, the tractive effort and resistance equilibrium can be written as

$$\frac{T_p i_g i_o \eta_t}{r_d} = M_v g f_r cos\alpha + \frac{1}{2}\,\rho_a\, C_D\, A_f V^2 + M_v g\mathrm{i} \rightarrow 3$$

$$\text{Thus, } i = \frac{\left(T_p i_g i_o \eta_t / r_d\right) - M_v g f_r - \left(\frac{1}{2}\,\rho_a\, C_D\, A_f V^2\right)}{M_v g} = \mathrm{d}\text{-}\ f_r \rightarrow 4$$

$$\text{Where } d = \frac{F_t - F_w}{M_v g} = \frac{\left(T_p i_g i_o \eta_t / r_d\right) - \left(\frac{1}{2}\,\rho_a\, C_D\, A_f V^2\right)}{M_v g} \rightarrow 5$$

where d is called Performance factor.

If the grade is large then gradeability of the vehicle can be

$$\text{Sin } \alpha = \frac{d - f_r\sqrt{d^2 + f_r^2}}{1 + f_r^2} \rightarrow 6$$

Acceleration Performance

- The acceleration performance of a vehicle is usually described by its acceleration time and the distance covered from zero speed to a certain high speed (zero to 96 km/h or 60 mph, for example) on level ground.
- Acceleration of the vehicle

$$a = \frac{dV}{dt} = \frac{F_t - F_f - F_w}{M_v g} = \frac{\left(T_p i_g i_o \eta_t / r_d \right) - M_v g f_r - \left(\frac{1}{2} \rho_a C_D A_f V^2 \right)}{M_v g} = \frac{g}{\delta} (\text{d-} f_r) \rightarrow 7$$

- where δ is called the mass factor,
- considering the equivalent mass increase due to the angular moments of the rotating components. The mass factor can be written as

$$\delta = 1 + \frac{I_w}{M_v r_d^2} = \frac{i_0^2 i_g^2 I_P}{M_v r^2} \rightarrow 8$$

- where *Iw* → the total angular moment of the wheels and
- *Ip* is the total angular moment of the rotating components associated with the power plant.

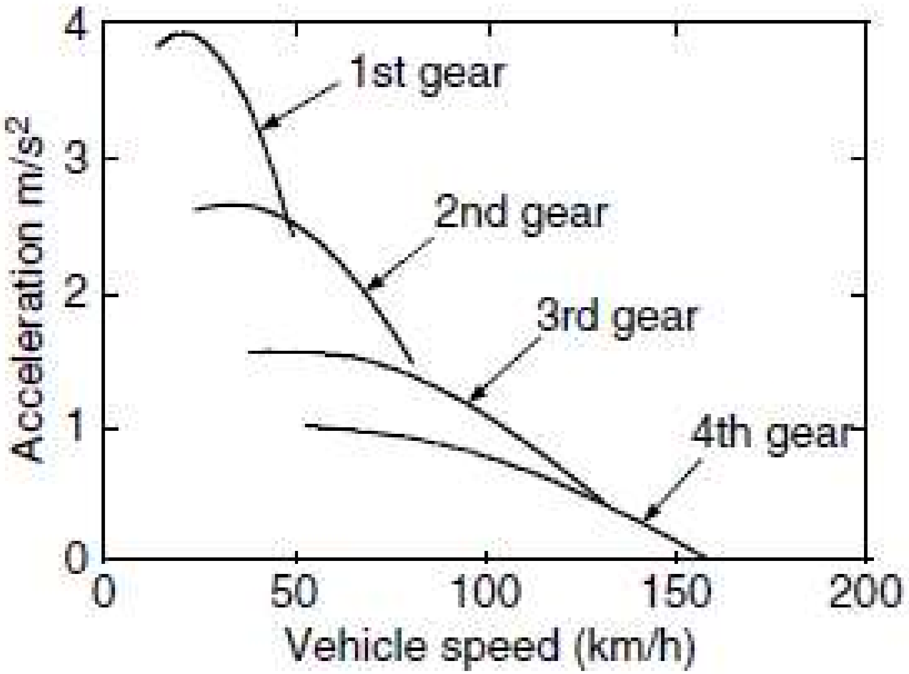
Acceleration Performance

- Calculation of the mass factor, δ, requires knowing the values of the mass moments of inertia of all the rotating parts. In the case where these values are not known, the mass factor, δ, for a passenger car would be estimated using the following empirical relation:

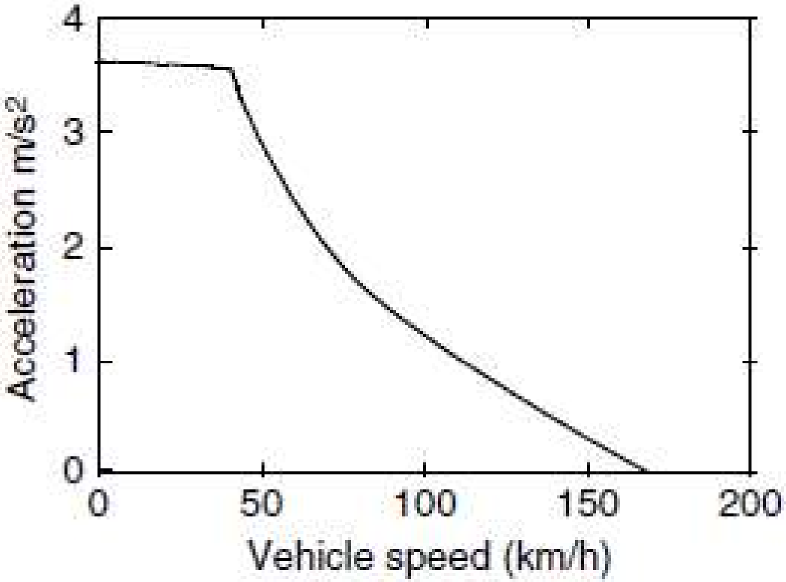
$$\delta = 1+\delta_1 + \delta_2\, i_0^2 i_g^2 \rightarrow 9$$

- where δ1 represents the second term on the right-hand side of equation 8 , with a reasonable estimate value of 0.04, and δ2 represents the effect of the power plant-associated rotating parts, and has a reasonable estimate value of 0.0025.

Acceleration Performance



Acceleration of a gasoline engine-powered vehicle with four-gear transmission



Acceleration of an electric machine-powered vehicle with single-gear transmission

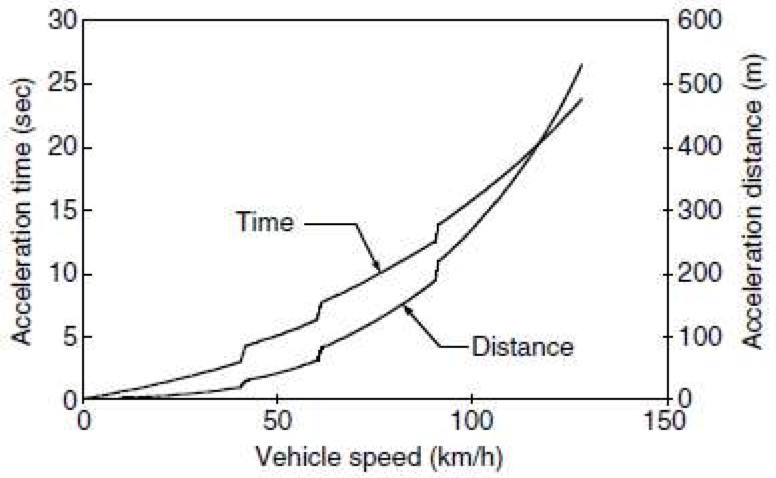
Acceleration Performance

- From the above equations, the acceleration time ta and distance Sa , from the low speed V1 to high speed V2 can be written as

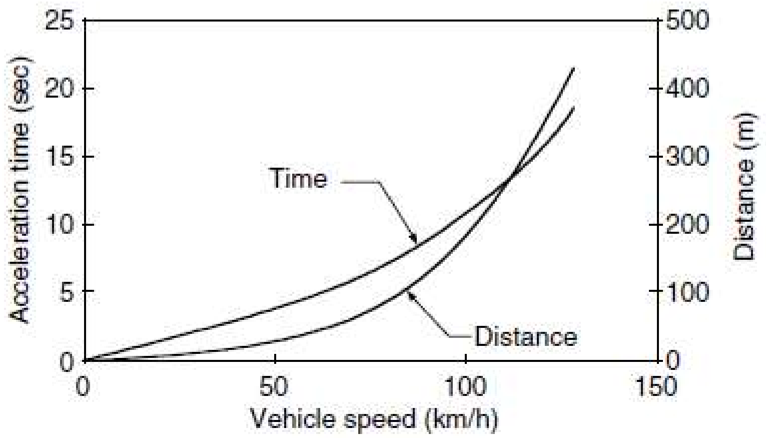
$$t_a = \int_{v_1}^{v_2} \frac{M_v \delta V}{\left({}^{T_p i_g i_o \eta_t}/_{r_d}\right) - M_v g f_r - (\frac{1}{2}\,\rho_a\, C_D\, A_f V^2)} \mathrm{dV} \rightarrow 10$$

and $$S_a = \int_{v_1}^{v_2} \frac{M_v \delta}{\left({}^{T_p i_g i_o \eta_t}/_{r_d}\right) - M_v g f_r - (\frac{1}{2}\,\rho_a\, C_D\, A_f V^2)} \mathrm{dV} \rightarrow 11$$

Acceleration Performance



Acceleration time and distance along with vehicle speed for a gasoline engine-powered passenger car with four-gear transmission



Acceleration time and distance along with vehicle speed for an electric machine-powered passenger car with single-gear transmission

III Year B. Tech. EEE II-Semester

Electric & Hybrid Vehicles

Course Code: PE116CW 3

(Professional Elective-II)

Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

Unit1:
Introduction to Hybrid Electric vehicles

Introduction:

- Introduction to Hybrid Electric vehicles:
  - History of Hybrid Electric Vehicles
  - Social and environmental importance of Hybrid and Electric vehicles
- Vehicle Fundamentals:
  - Vehicle Resistance
  - Dynamic Equation
  - Tire-Ground Adhesion and Maximum Tractive effort
  - Power Train Tractive effort and Vehicle speed
  - Vehicle power Plant and Transmission Characteristics
  - Vehicle Performance
  - **Operating Fuel Economy braking Performance**

Operating Fuel Economy

- The fuel economy of a vehicle is evaluated by the amount of fuel consumption per 100 km traveling distance (litres /100 km) or mileage per gallon fuel consumption (miles/gallon), which is currently used in the U.S.
- The operating fuel economy of a vehicle depends on a number of factors, including fuel consumption characteristics of the engine, gear number and ratios, vehicle resistance, vehicle speed, and operating conditions.

Fuel Economy Characteristics of Internal Combustion Engines

- The fuel economy characteristic of an internal combustion engine is usually evaluated by the amount of fuel per kWh energy output, which is referred to as the specific fuel consumption (g/kWh).
- The typical fuel economy characteristic of a gasoline engine is shown in Figure1.
- The fuel consumption is quite different from one operating point to another.
- The optimum operating points are close to the points of full load (wide-opened throttle).
- The speed of the engine also has a significant influence on fuel economy.
- With a given power output, the fuel consumption is usually lower at low speed than at high speed.
- For instance, when the engine shown in Figure 1 has a power output of 40 kW, its minimum specific fuel consumption would be 270 g/kWh at a speed of 2080 rpm.

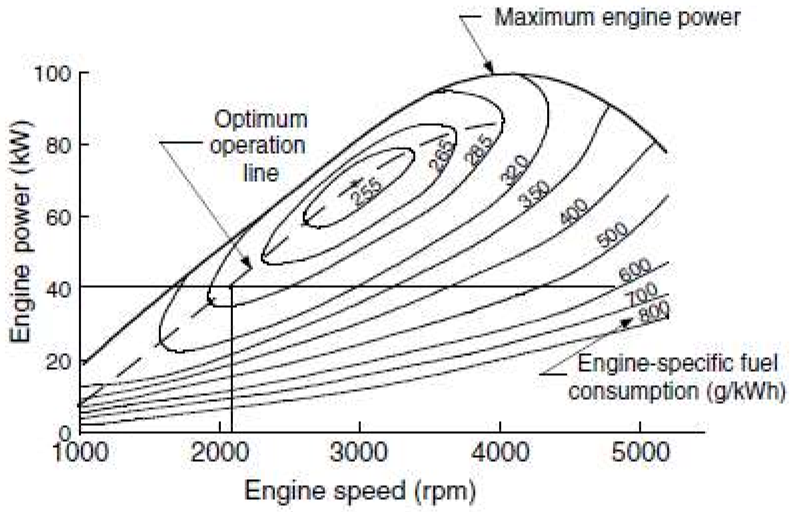


Fig 1: Fuel economy characteristics of a typical gasoline engine

Fuel Economy Characteristics of Internal Combustion Engines

- For a given power output at a given vehicle speed, the engine operating point is determined by the gear ratio of the transmission.
- Gear ratio is chosen to operate the engine at optimum operating point.
- This advantage has stimulated the development of a variety of continuous variable transmissions, including frictional drive, hydrodynamic drives, hydrostatic drives, and hydromechanical variable drive.

Calculation of Vehicle Fuel Economy

- Vehicle fuel economy can be calculated by finding the load power and the specific fuel consumption of the engine.
- The engine power output is always equal to the resistance power of the vehicle, that is

$$P_e = \frac{V}{\eta_t}(F_f + F_w + F_g + M_v \delta \frac{dV}{dt}) \rightarrow 1$$

So $P_e = \frac{V}{1000\eta_t}(M_v g f_r cos\alpha + \frac{1}{2}\rho_a C_D A_f V^2 + M_v g sin\alpha + M_v g \frac{dV}{dt})$ KW $\rightarrow 2$

The engine speed, related to vehicle speed and gear ratio, can be expressed as

$$N_t = \frac{30 V i_g i_0}{\pi r_d} \rightarrow 3$$

Calculation of Vehicle Fuel Economy

- After determination of the engine power and speed by equ 1and equ 2, the value of the specific fuel consumption, *ge*, can be found in the graph of the engine fuel economy characteristics as shown in Figure 1.
- The time rate of fuel consumption can be calculated by

$$Q_{fr} = \frac{P_e g_e}{1000\,\gamma_f} \rightarrow 4$$

where, g_e is the specific fuel consumption of the engine in g/KWh

γ_f is the mass density of the fuel in kg/l

- The total fuel consumption within a total distance, *S*, at a constant cruising speed, *V*, is obtained by

$$Q_s = \frac{P_e g_e}{1000\,\gamma_f} \frac{S}{V} \rightarrow 5$$

Calculation of Vehicle Fuel Economy

- Fig.2 shows an example of the fuel economy characteristics of a gasoline vehicle at constant cruising speed on level ground.
- This figure indicates that at high speeds, the fuel consumption increases because the aerodynamic resistance power increases with the speed cubed.
- This figure also indicates that with a high-speed gear (small gear ratio), the fuel economy of the vehicle can be enhanced due to the reduced engine speed at a given vehicle speed and increased gear ratio.

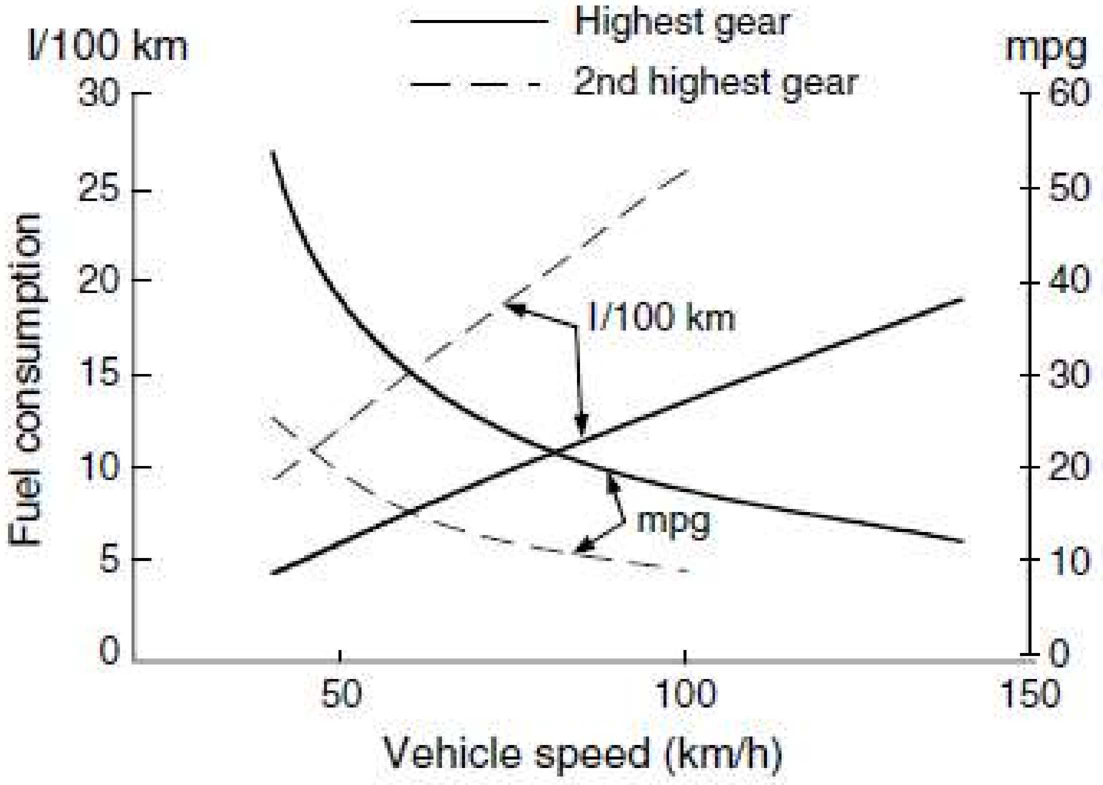


Fig 2: Fuel economy characteristics of a typical vehicle at constant speed

Calculation of Vehicle Fuel Economy

- Fig3 shows the operating points of an engine at constant vehicle speed, with the highest gear and the second highest gear.
- It indicates that the engine has a much lower operating efficiency in low gear than in high gear.
- This is the reason why the fuel economy of a vehicle can be improved with more gear transmission and continuous variable transmission.
- It should be noted that because of the complexity of vehicle operation in the real world, fuel consumption at constant speed cannot accurately represent fuel consumption for a vehicle under real driving conditions. Thus, various drive cycles have been developed to simulate real driving conditions.

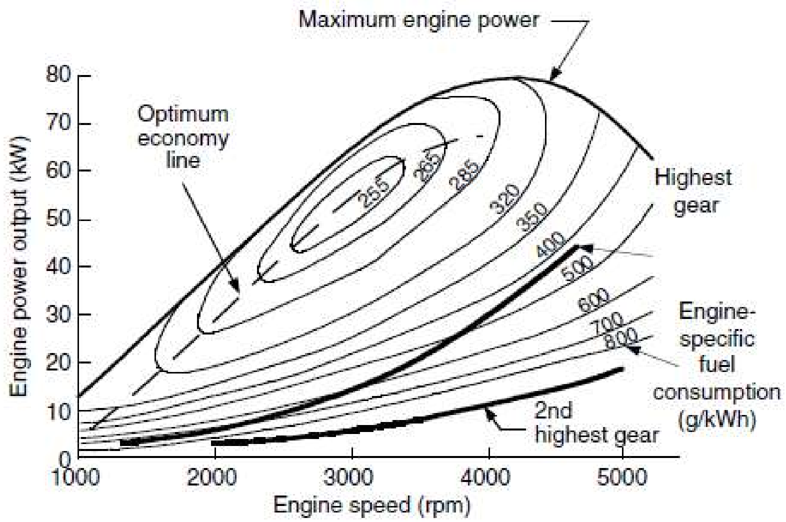


Fig 3: Operating point of an engine at constant speed with highest gear and second highest gear

Driving cycle- EPA FTP 75

- The drive cycles are usually represented by the speed of the vehicle along with the relative driving time.
- Figure 2.31 shows the urban and highway drive cycles of EAP FTP75 used in the U.S.
- To calculate fuel consumption in a drive cycle, the total fuel consumption can be obtained by the summation of fuel consumption in each time interval, Δti
- $$Q_{tc} = \sum_i \frac{P_{ei} g_{ei}}{1000\, \gamma_f} \Delta\, t_i \rightarrow 6$$

P_{ei} is the average power of the engine in the ith time interval in KW
g_{ei} is the average specific fuel consumption of the engine in g/KWH
Δti is the ith time interval in h.

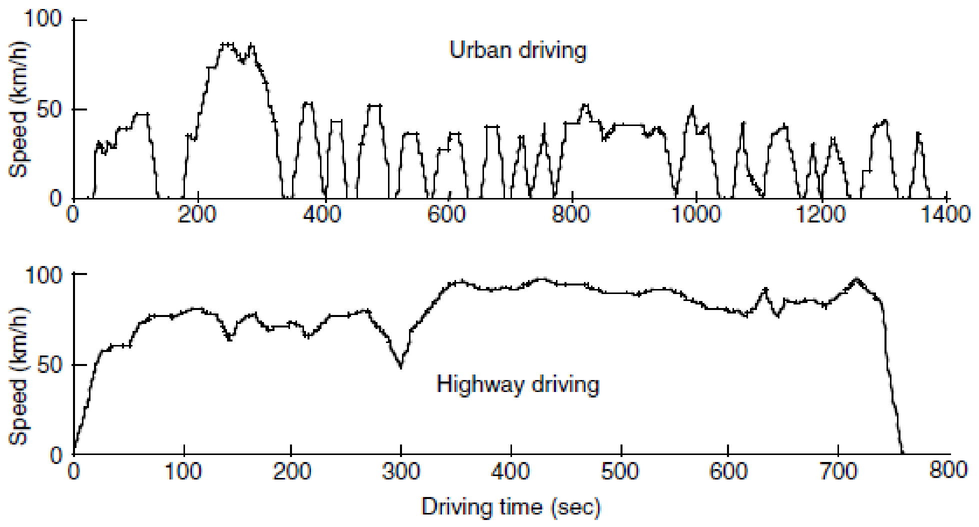


Fig. 4 EPA FTP75 urban and highway drive cycles

Basic Techniques to Improve Vehicle Fuel Economy

- The effort to improve the fuel economy of vehicles has been an ongoing process in the automobile industry. Fundamentally, the techniques usedinclude the following aspects:

1. *Reducing vehicle resistance*
2. *Improving engine operation efficiency*
3. *Properly matched transmission*
4. *Advanced drive trains*

- (1) *Reducing vehicle resistance*: Using light materials, advanced manufacturing technologies can reduce the weight of vehicles, in turn reducing the rolling resistance and inertial resistance in acceleration and therefore reducing the demanded power on the engine. The use of advanced technologies in tire production is another important method of reducing the rolling resistance of vehicles. For instance, steel wire plied radial tires have a much lower rolling resistance coefficient than conventional bias ply tires. Reducing aerodynamic resistance is also quite important for improving the fuel economy at high speeds. This can be achieved by using a flow shaped body style, a smooth body surface, and other techniques. Furthermore, improving transmission efficiency can reduce energy losses in the transmission. Proper transmission construction, good lubrication, proper adjustment and tightening of moving parts in the transmission, and so on will achieve this purpose.

Basic Techniques to Improve Vehicle Fuel Economy

- *(2) Improving engine operation efficiency*: Improving engine operation efficiency has the potential to contribute to the improvement of vehicle fuel economy. There are many effective advanced techniques, such as accurate air/fuel ratio control with computer controlled fuel injection, high thermal isolated materials for reducing thermal loss, varying ignition-timing techniques, active controlled valve and port, etc.
- (3) *Properly matched transmission*: The parameters of the transmission, especially gear number and gear ratios, have considerable influence on the operating fuel economy as described previously. In the design of the transmission, the parameters should be constructed such that the engine will operate close to its fuel optimum region.
- (4) *Advanced drive trains*: Advanced drive trains developed in recent years, such as new power plants, various hybrid drive trains, etc., may greatly improve the fuel economy of vehicles. Fuel cells have higher efficiency and lower emissions than conventional internal combustion engines. Hybridization of a conventional combustion engine with an advanced electric motor drive may greatly enhance the overall efficiency of vehicles.

Braking Performance

- The braking performance of a vehicle is undoubtedly one of the most important characteristics that affect vehicle safety.
- In urban driving, a significant amount of energy is consumed in braking.
- In recent years, more and more electric drives have been involved in vehicle traction, such as electric vehicles, hybrid electric vehicles, and fuel cell-powered vehicles.
- The electrification of the vehicle drive train makes it feasible to recover some of the energy lost in braking.
- This technology is usually referred to as regenerative braking. A well-designed regenerative braking system not only improves vehicle efficiency but also potentially improves braking performance.

Braking Force

Fig5(a) shows a wheel during braking.
The brake pad is pressed against the brake plate, thus developing a frictional torque on the brake plate.
This braking torque results in a braking force in the tire–ground contact area.
It is just this braking force that tries to stop the vehicle. The braking force can be expressed as

$F_b = \frac{T_b}{r_b}$ →7

The braking force increases with an increase in braking torque.
However, when the braking force reaches the maximum braking force that the tire–ground adhesion can support, it will not increase further, although the
braking torque may still increase as shown in Fig5(b). This maximum braking force limited by the adhesive capability can be expressed as $F_{bmax} = \mu_b W_f$ →8

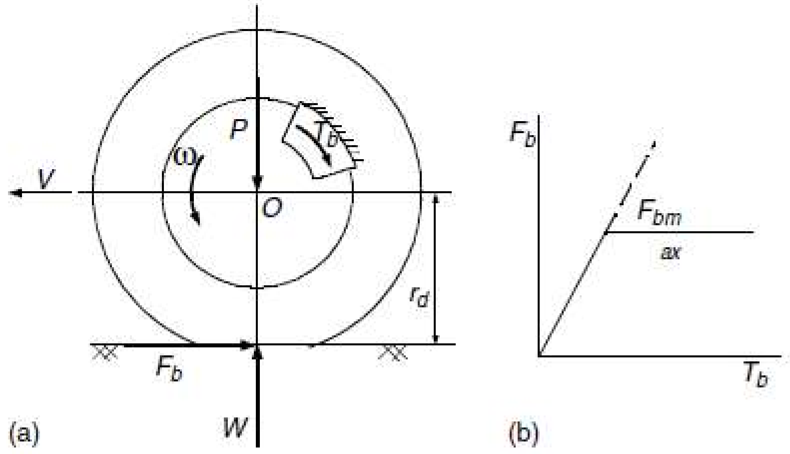


Fig 5(a) Braking torque and braking force, and (b) relationship between braking torque and braking force

Braking Distribution on Front and Rear Axles

- Fig. 6 shows the forces acting on a vehicle during braking on a flat road. Rolling resistance and aerodynamic drag are ignored in this figure, because they are quite small compared to the braking forces. j is the deceleration of the vehicle during braking

Deceleration is expressed as $j = \frac{F_{bf}+F_{br}}{M_v}$ →9

F_{bf} is the front wheel braking force and F_{br}

Is the rear wheel braking force.

Max. braking force is limited by the tire-ground adhesion and is proportional to the normal load acting on the tire.

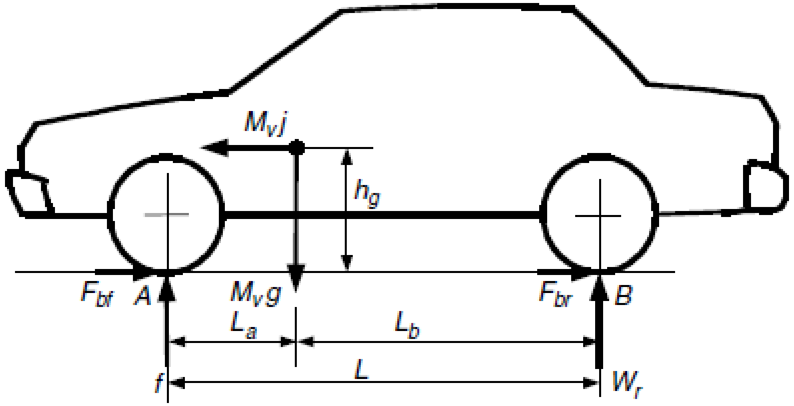


Fig 6: Force acting on a vehicle during braking on a flat road

Braking Distribution on Front and Rear Axles

- The maximum braking force is limited by the tire–ground adhesion and is proportional to the normal load acting on the tire. Thus, the actual braking force developed by the brake torque should also be proportional to the normal load so that both the front and the rear wheels obtain their maximum braking force at the same time.
- During braking, there is load transfer from the rear axle to the front axle.
- By considering the equilibrium of moments about the front and rear tire–ground contact points A and B, the normal loads on the front and rear axles, *Wf* and *Wr*, can be expressed as

$$W_f = \frac{M_v g}{L}\left(L_b + h_g \frac{j}{g}\right) \rightarrow 10$$

And $$W_r = \frac{M_v g}{L}\left(L_a + h_g \frac{j}{g}\right) \rightarrow 11$$

Where j is the deceleration of the vehicle.

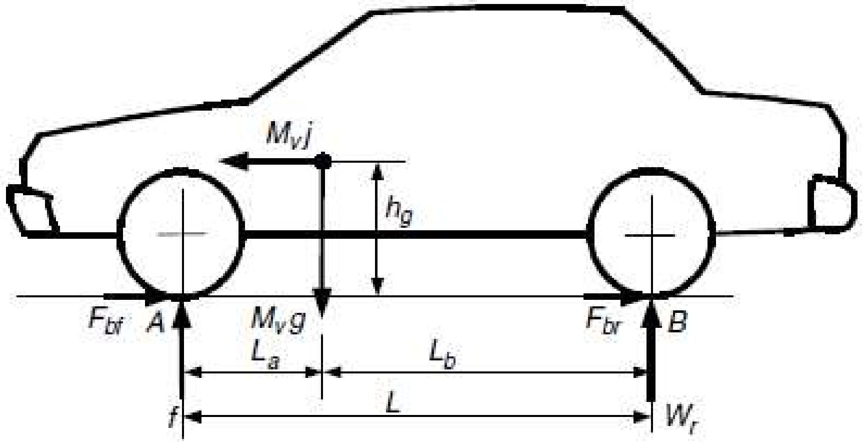


Fig 7: Force acting on a vehicle during braking on a flat road

Braking Distribution on Front and Rear Axles

- The braking forces of the front and rear axle should be proportional to their normal load, respectively; thus, one obtains

$$\frac{F_{bf}}{F_{br}} = \frac{W_f}{W_r} = \frac{L_b + {}^{h_g j}/_{g}}{L_a - {}^{h_g j}/_{g}} \rightarrow 12$$

Combining equ 9 and 12, the ideal braking forces on front and rear axle can be shown in fig.8

- The ideal braking force distribution curve (simply, *I* curve) is a nonlinear hyperbolic curve. If it is desired for the front and rear wheels to lock up at the same time on any road, the braking force on the front and rear axle must closely follow this curve.

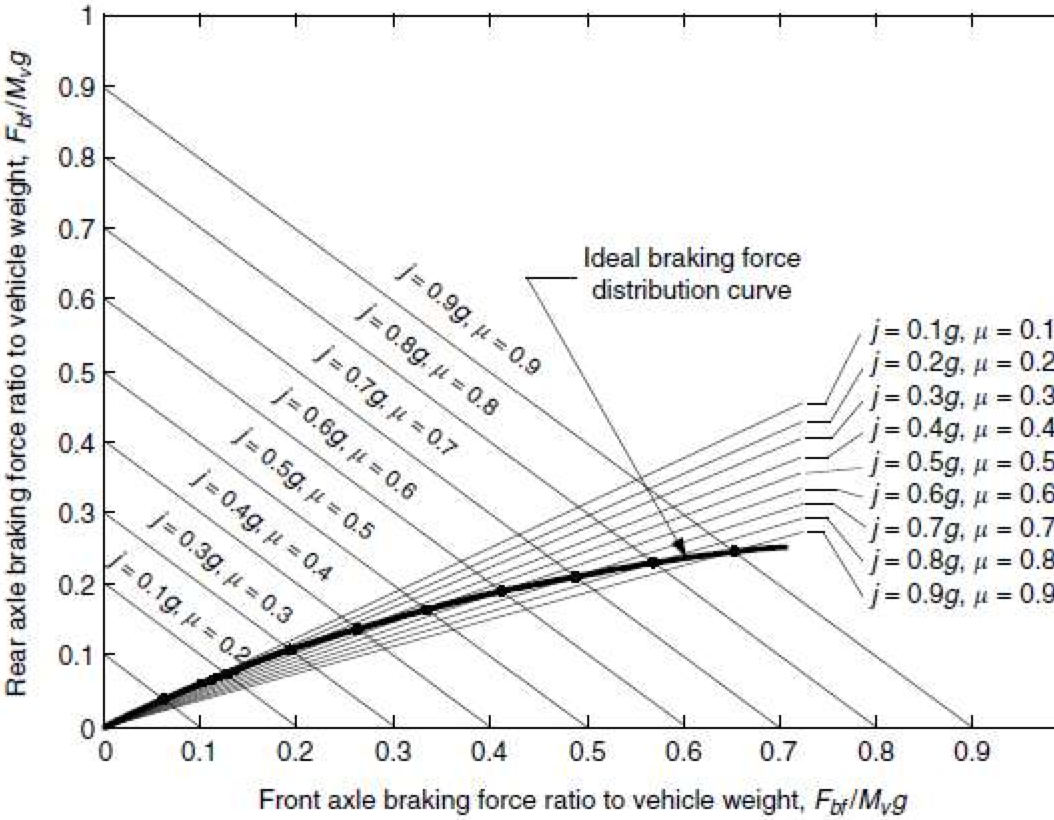


Fig 8: Ideal braking force distribution curve on the front and rear axles

Braking Distribution on Front and Rear Axles

- The antilock braking system (ABS), developed in recent years, can effectively prevent wheels from locking up.
- This system employs speed sensors to detect the wheel rotating speed. When a wheel lockup is detected, the braking pressure control system reduces the pressure and brings the wheel back to its rotation

III Year B.Tech. EEE II-Semester

Electric & Hybrid Vehicles

Course Code: PE116CW 3

(Professional Elective-II)

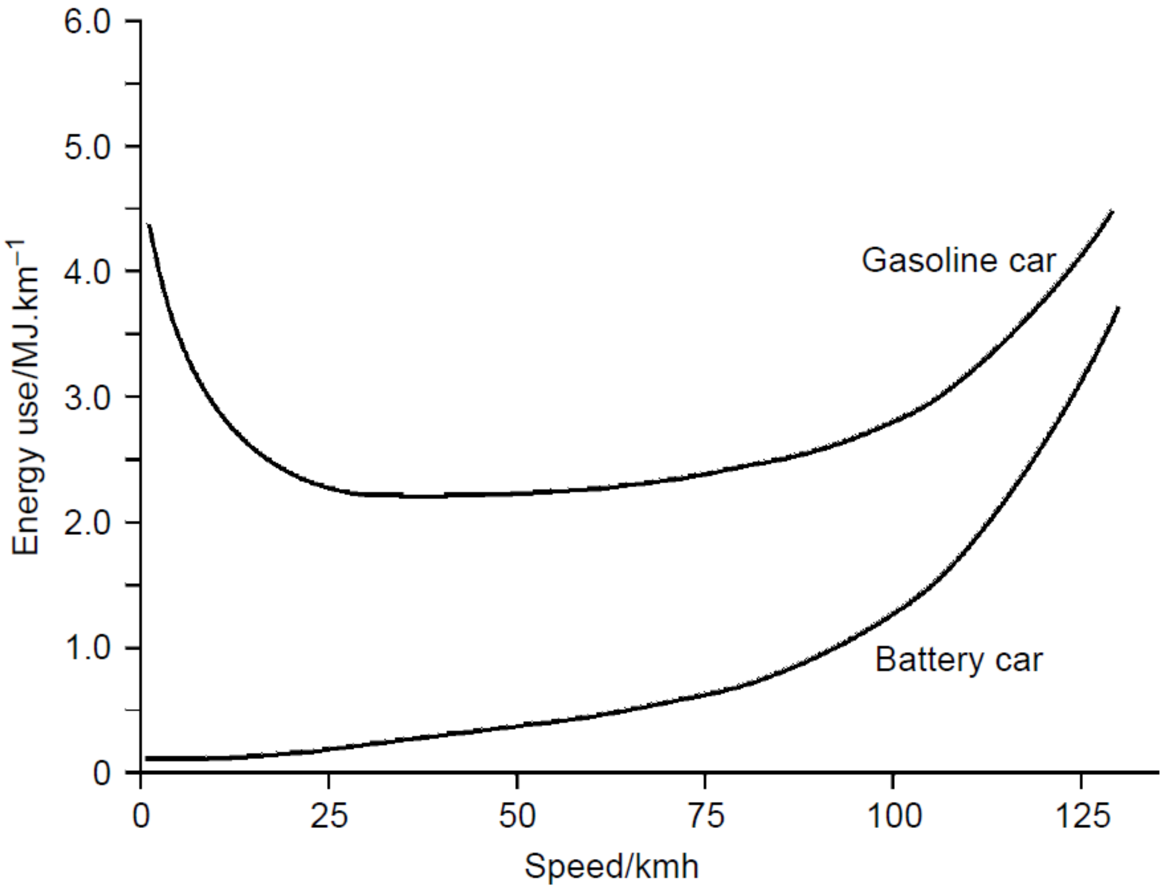
Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

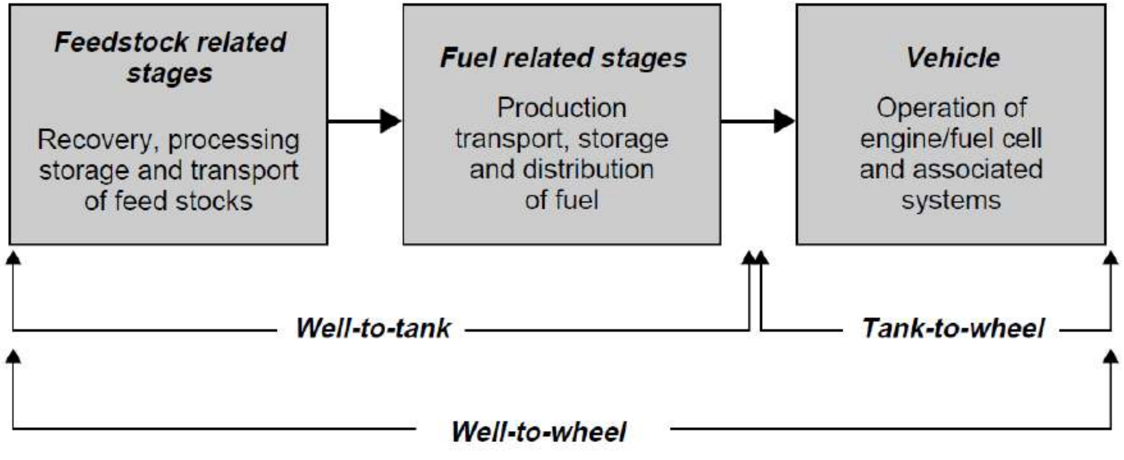
UNIT 2: (~8 Lecture Hours)

- Energy storage:
- **Introduction to energy storage requirements in hybrid and electric vehicles.**
- **Electro chemical batteries and its analysis,**
- Ultra capacitors and its analysis,
- Ultra high speed flywheels and its analysis,
- Hybridization of Energy storages.

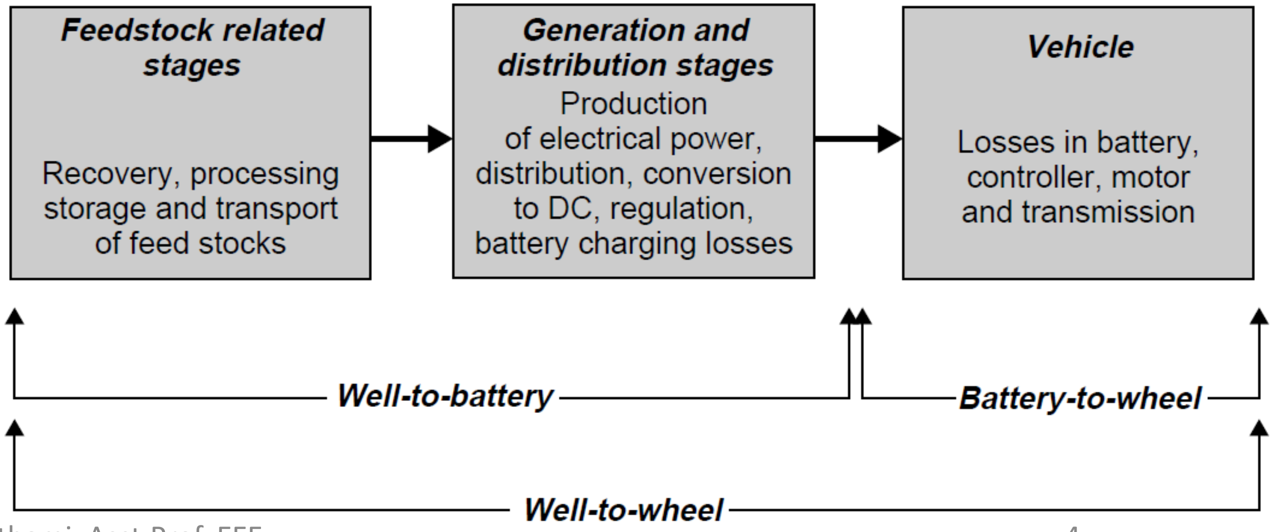
Energy Usage in ICE vs EV



Well- to- wheel stages



(a) Fuelled vehicles



Energy storage

- "Energy storages: the devices that store energy, deliver energy outside (discharge), and accept energy from outside (charge).
- There are several types of energy storages that have been proposed for electric vehicle (EV) and hybrid electric vehicle (HEV) applications.
- These energy storages, so far, mainly include chemical batteries, ultracapacitors or supercapacitors, and ultrahigh-speed flywheels.
- The fuel cell, which essentially is a kind of energy converter.
- There are a number of requirements for energy storage applied in an automotive application, such as specific energy, specific power, efficiency, maintenance requirement, management, cost, environmental adaptation and friendliness, and safety. For allocation on an EV, specific energy is the first consideration since it limits the vehicle range. On the other hand, for HEV applications, specific energy becomes less important and specific power is the first consideration, because all the energy is from the energy source (engine or fuel cell) and sufficient power is needed to ensure vehicle performance, particularly during acceleration, hill climbing, and regenerative braking. Of course, other requirements should be fully considered in vehicle drive train development.

Electrochemical Batteries : Structure

- Commonly referred as "batteries
- Electrochemical devices convert electrical energy into potential chemical energy during charging, and convert chemical energy into electric energy during discharging.
- A "battery" is composed of several cells stacked together.
- A cell is an independent and complete unit that possesses all the electrochemical properties.
- Basically, a battery cell consists of three primary elements: two electrodes (positive and negative) immersed into an electrolyte as shown in Figure 1.

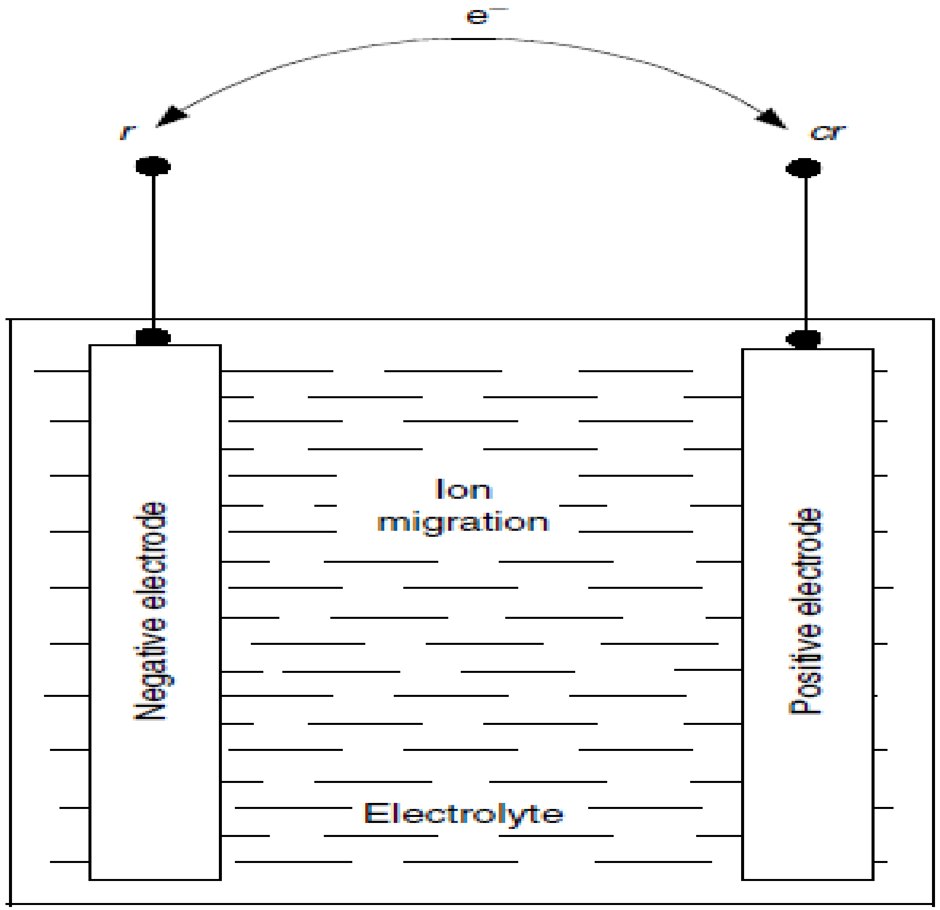


Fig.1 A typical electrochemical battery cell

Electrochemical Batteries: C-rate

- Battery manufacturers usually specify the battery with coulometric capacity (amp-hours), which is defined as the number of amp-hours gained when discharging the battery from a fully charged state until the terminal voltage drops to its cut-off voltage, as shown in Figure 2.
- It should be noted that the same battery usually has a different number of amp-hours at different discharging current rates.
- Generally, the capacity will become smaller with a large discharge current rate, as shown in Figure 3.
- Battery manufacturers usually specify a battery with a number of amp-hours along with a current rate.
- For example, a battery labeled 100 Ah at C5 rate has a 100 amp-hour capacity at 5 hours discharge rate (discharging current100/5 =20 A).

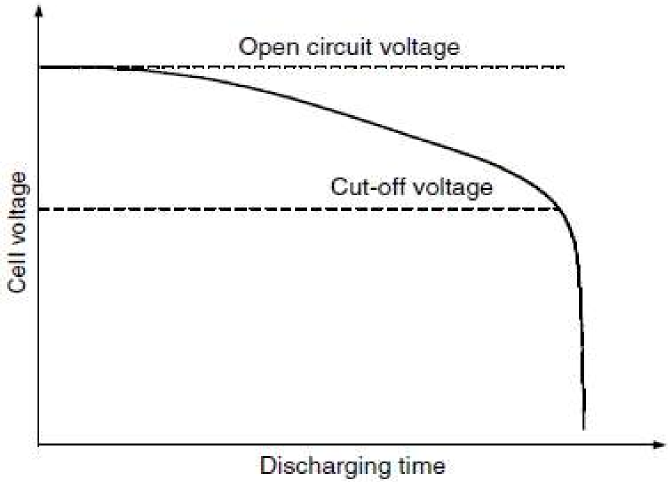


Fig2: Cut-off voltage of a typical battery

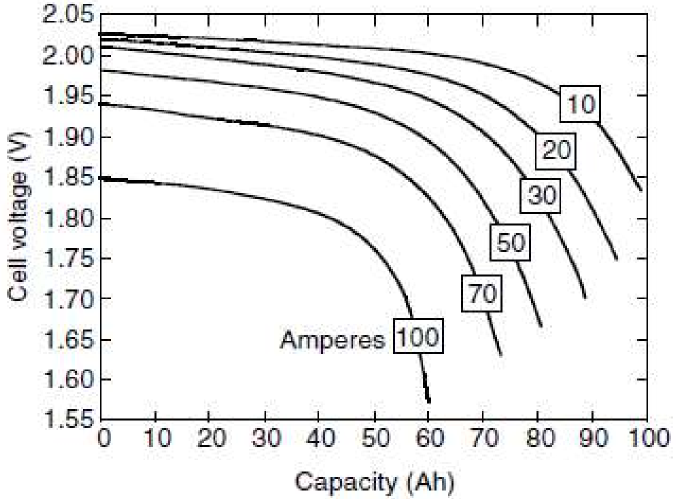


Fig3: Discharge characteristics of a lead-acid battery

Electrochemical Batteries: SOC

- SOC is defined as the ratio of the remaining capacity to the fully charged capacity.
- With this definition, a fully charged battery has an SOC of 100% and a fully discharged battery has an SOC of 0%.
- Note:However, the term "fully discharged" sometimes causes confusion because of the different capacity at different discharge rates and different cut-off voltage (refer to fig.3).

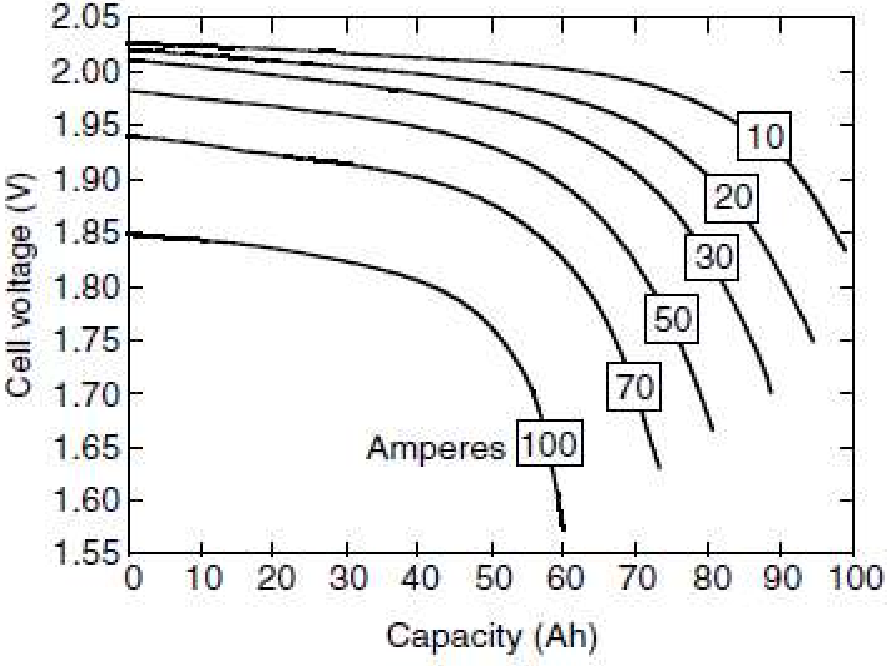


Fig3: Discharge characteristics of a lead-acid battery

Electrochemical Batteries: SOC

- The change in SOC in a time interval, *dt*, with discharging or charging current *i* may be expressed as

$$\Delta SOC = \frac{i\,dt}{Q(i)} \rightarrow 1$$

Where $Q(i)$ is amp-hour capacity of the battery at current rate i.

For discharging, i is positive, and for charging, i is negative.

So $$SOC = SOC_o - \int \frac{i\,dt}{Q(i)} \rightarrow 2$$

Where SOC_o is the initial value of the SOC.

Energy delivered by the battery can be expressed as

$$EC = \int_0^t V(i, SOC)\, i(t)\, dt \rightarrow 3$$

$V(i, SOC)$ is the voltage at the battery terminals, which is a function of the battery current and SOC.

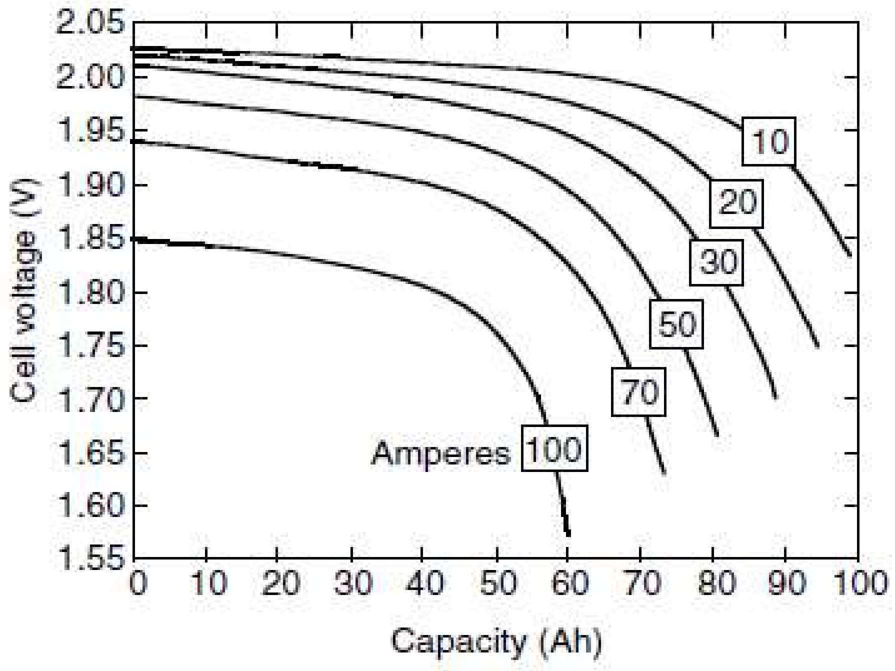


Fig3: Discharge characteristics of a lead-acid battery

Gibbs free energy

- It is a Thermodynamic potential that can be used to calculate the maximum reversible work that may be performed by a thermodynamic system at a constant temperature and pressure. It is minimized when a system reaches chemical equilibrium at constant pressure and temperature.
- Gibbs free energy is also called available energy.
- The Gibbs free energy is one of the most important thermodynamic functions for the characterization of a system.
- It is a factor in determining outcomes such as the voltage of an electrochemical cell, and the equilibrium constant for a reversible reaction.
- **Gibbs Free energy:** The available energy of a substance that can be used in a chemical transformation or reaction. Substances tend to transform into other substances that have less Gibbs free energy.
- The change of Gibbs free energy predicts whether a chemical reaction will occur spontaneously.
- Change in Gibbs free energy ΔG, is known to equal the electrical work (i.e., energy) given off by the battery or galvanic cell under optimum.

Thermodynamic Voltage

- The thermodynamic voltage of a battery cell is depended on the energy released and the number of electrons transferred in the reaction.
- The energy released by the battery cell reaction is given by the change in Gibbs free energy, ΔG, usually expressed in per mole quantities.
- The change in Gibbs free energy in a chemical reaction can be expressed as

$$\Delta G = \sum_{products} G_i - \sum_{Reactants} G_j \rightarrow 9$$

where G_i and G_j are the free energy in species i of products and species j of reactants.

Thermodynamic Voltage

In a reversible process, ΔG is completely converted into electric energy, that is,

$$\Delta G = -\,nF\,V_r \rightarrow 10$$

n is the no. of electrons transferred in the reaction

F = 96,495 is the Faraday constant in coulombs per mole

V_r is the reversible voltage of the cell.

At standard condition (25 degree temperature and 1 atm pressure) the open circuit (reversible) voltage of a battery cell can be expressed as

$$V_r^0 = -\frac{\Delta G^0}{nF} \rightarrow 11$$

where ΔG^0 *is the change in Gibbs free energy* at standard conditions.

Thermodynamic Voltage

- The change of free energy, and thus the cell voltage, in a chemical reaction is a function of the activities of the solution species. From equation 10 and the dependence of ΔG on the reactant activities, the *Nernst relationship* is derived as

$$V_r = V_r^0 - \frac{RT}{\text{nF}} \ln \left[\frac{\pi(activities\ of\ products}{\pi(activities\ of\ reactants)} \right] \rightarrow 12$$

Where R is the universal gas constant 8.31 J/mol K and T is absolute temperature in K.

Specific Energy

- It is defined as the energy capacity per unit battery weight(Wh/Kg).
- The theoretical specific energy is the maximum energy that can be generated per unit total mass of the cell reactant.
- The energy in a battery cell can be expressed by the Gibbs free energy ΔG. With respect to theoretical specific energy, only the effective weights (molecular weight of reactants and products) are involved; then

$$\mathrm{E}_{spe,,theo} = -\frac{\Delta G}{3.6\sum M_i} = \frac{nFV_r}{3.6\sum M_i} \text{ (wh/kg)} \rightarrow 13$$

Where $\sum M_i$ is the sum of the molecular weight of the individual species involved in the battery reaction.

- Eg: In lead acid battery, V_r = 2.03v, n=2 and $\sum M_i$ = 642g
- So $\mathrm{E}_{spe,,theo}$ = 170 wh/kg

Choice of electrodes

- Ideal electrodes are highly electronegative element and highly electropositive element, both of low atomic weight.
- Hydrogen, lithium, sodium would be the best choice for –ve reactants.
- And lighter halogens, oxygen, or sulfur would be the choice for positive.
- To put such couples together in a battery requires electrode designs for effective utilization of the contained active materials, as well as electrolytes of high conductivity compatible with the materials in both electrodes.
- These constraints result in oxygen and sulfur being used in some systems as oxides and sulfides rather than as the elements themselves.
- For operation at ambient temperature, aqueous electrolytes are advantageous because of their high conductivities.
- Here, alkali-group metals cannot be used as electrodes since these elements react with water.
- It is necessary to choose other metals, which have a reasonable degree of electro positivity, such as zinc, iron, or aluminum.
- When considering electrode couples, it is preferable to exclude those elements that have a low abundance in the earth's crust, are expensive to produce, or are unacceptable from a health or environmental point of view.

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

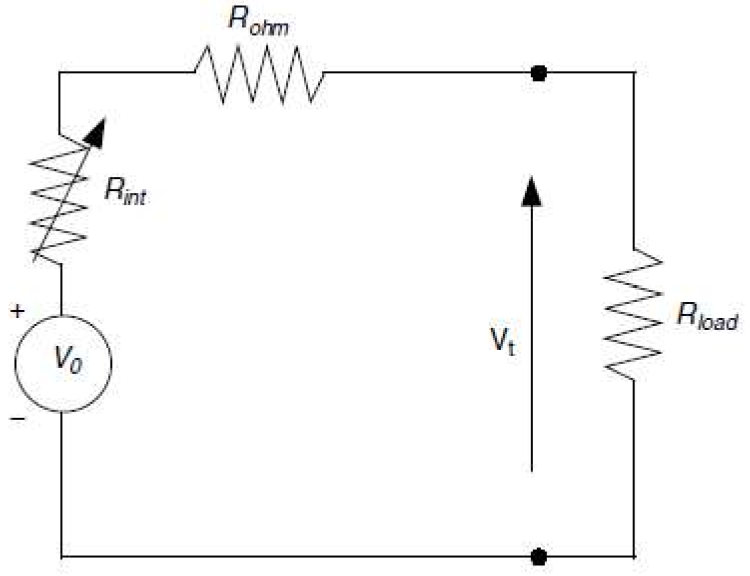
Battery ⊕	⊖	Cell Reaction: Charge ⇐	Discharge ⇒	Specific Energy (Wh/kg)
Acidic aqueous solution				
PbO_2	Pb	$PbO_2+2H_2SO_4+Pb$	⇔ $2PbSO_4+2H_2O$	170
Alkaline aqueous solution				
NiOOH	Cd	$2NiOOH+2H_2O+Cd$	⇔ $2Ni(OH)_2+Cd(OH)_2$	217
NiOOH	Fe	$2NiOOH+2H_2O+Fe$	⇔ $2Ni(OH)_2+Fe(OH)_2$	267
NiOOH	Zn	$2NiOOH+2H_2O+Zn$	⇔ $2Ni(OH)_2+Zn(OH)_2$	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]

[a]For a maximum value of $x-0.5$ and $y=0$.

Specific Power

- Specific power is defined as the maximum power of per unit battery weight that the battery can produce in a short period.
- Specific power is important in the reduction of battery weight, especially in high power demand applications, such as HEVs.
- The specific power of a chemical battery depends mostly on the battery's internal resistance. With the battery model as shown in Figure, the maximum power that the battery can supply to the load is

$$P_{peak} = \frac{V_0^2}{4(R_{ohm} + R_{int})}$$



Battery circuit model

Where Rohm is conductor resistance or ohmic resistance

Rint is internal resistance caused by chemical reaction.

Energy Efficiency

- Fig. shows the efficiency of the lead-acid battery during discharging and charging.
- The battery has high discharging efficiency with high SOC and high charging efficiency with low SOC.
- The net cycle efficiency has a maximum in the middle range of the SOC. Therefore, the battery operation control unit of an HEV should control the battery SOC in its middle range so as to enhance the operating efficiency and depress the temperature rise caused by energy loss.
- High temperature would damage the battery

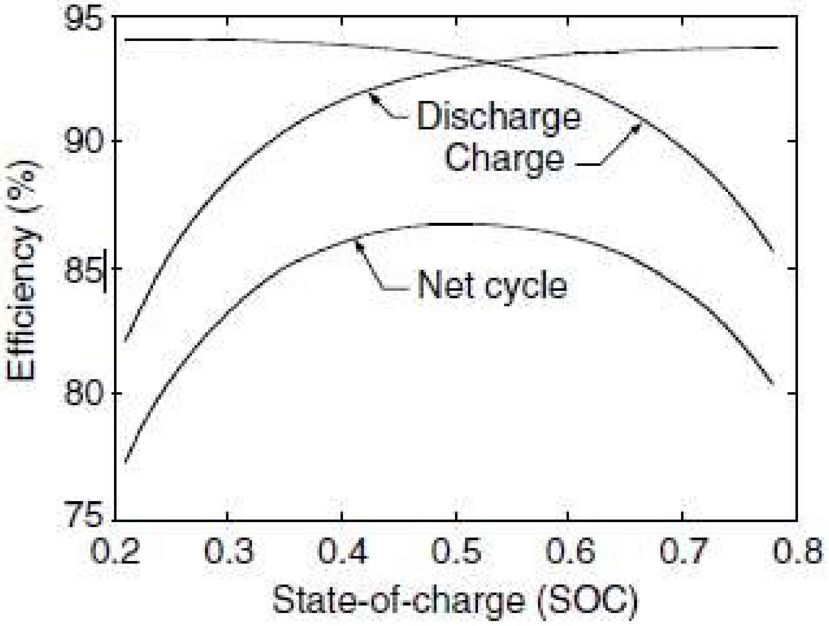
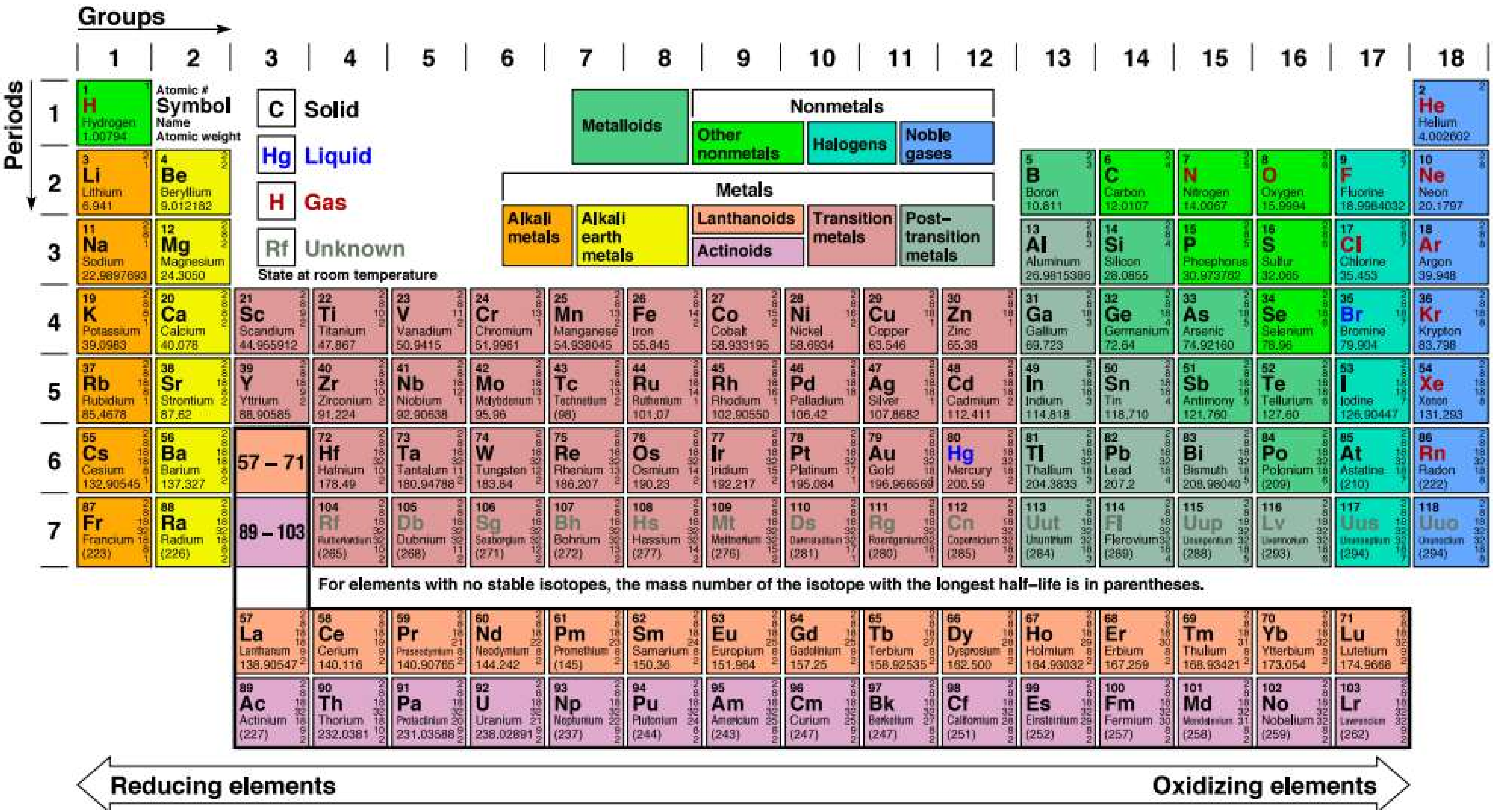


Fig: Typical battery charge and discharge efficiency

Periodic Table



Different batteries used in Electric vehicle

- Lead acid Batteries
- Nickel based batteries
  - Nickel/iron system
  - Nickel cadmium system
  - Nickel-Metal Hydrate (Ni-MH) Battery

- Lithium Based Batteries
  - Lithium- Polymer (Li-P) Battery
  - Lithium- Ion (Li-ion) Battery

Lead acid Batteries

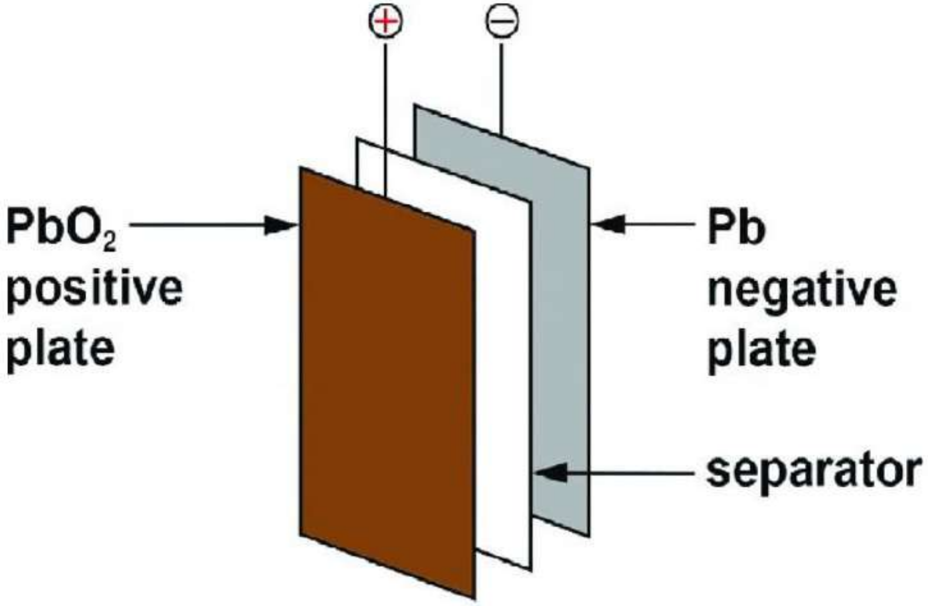
- Lead acid batteries are High power, inexpensive, safe, and reliable.
- But low specific energy, poor cold-temperature performance, and short calendar and cycle life impede their use.
- The presence of highly corrosive sulfuric acid is a potential safety hazard for vehicle occupants. Hydrogen released by the self-discharge reactions is another potential danger, since this gas is extremely flammable even in tiny concentrations.
- Hydrogen emission is also a problem for hermetically sealed batteries.

- Advanced high-power lead-acid batteries are being developed, but these batteries are only used in commercially available electric-drive vehicles for ancillary loads.

Lead Acid battery

- First Rechargeable battery
- Invented by French physicist Gaston Plante in year 1959
- Energy density: 80-90 Wh/ L
- Specific energy: 35-40 Wh/ Kg
- Specific Power: 180 Wh/ Kg
- Cycle Durability : < 350 cycles
- Charge/ discharge efficiency: 50-95%
- Self discharge rate 3-20% /Month

Lead Acid Battery



Pb + PbO2 + 2H2SO4 ⇌ 2PbSO4 + 2H2O

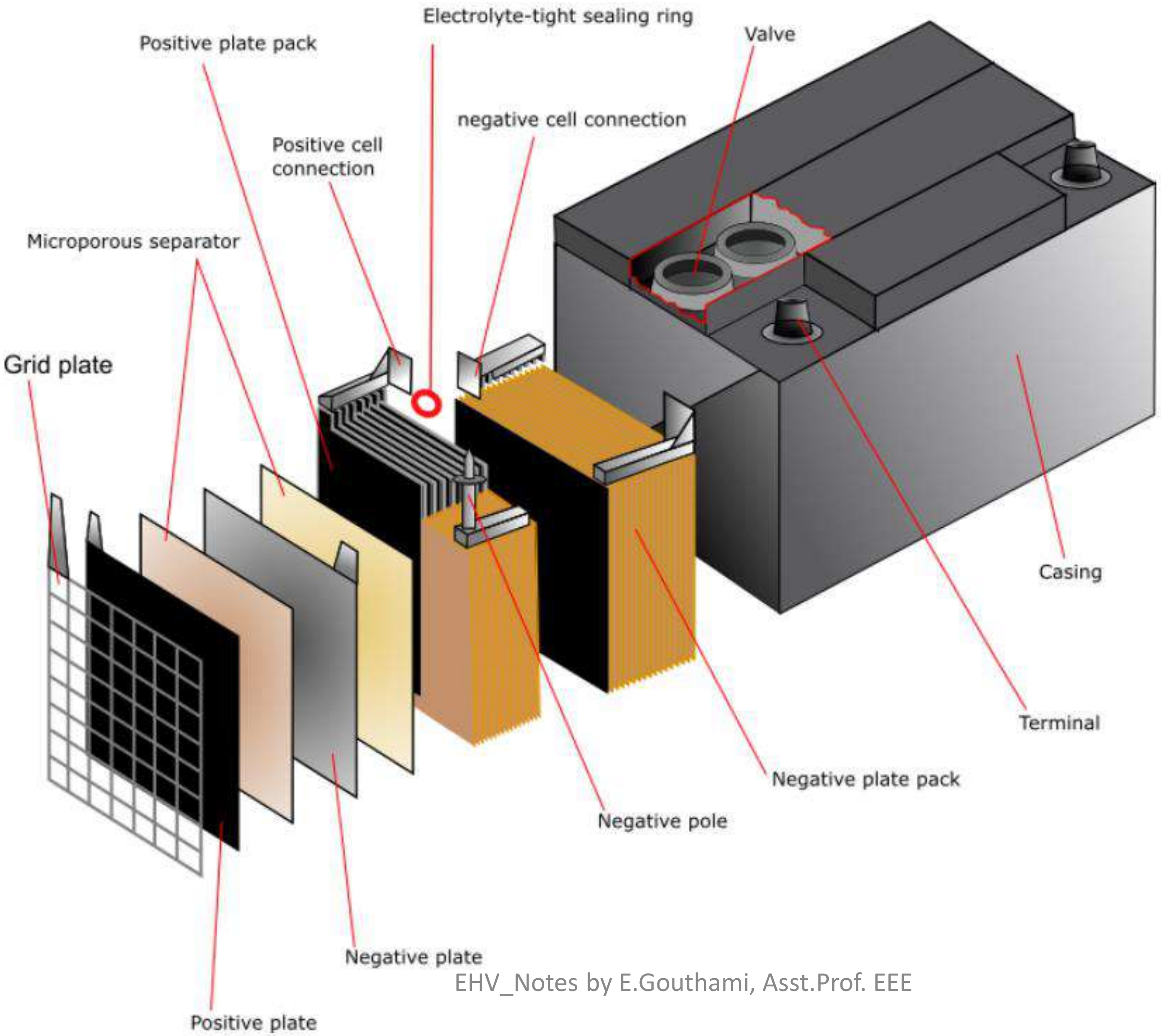
Anode: $PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$

Cathode: $PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e^-$

The overall reaction

$$Pb + PbO_2 + 2H_2SO_4 \underset{\text{Charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O$$

Lead Acid Battery: Construction



Electrochemical Reactions

- A lead-acid battery uses an aqueous solution of sulfuric acid ($2H^+ + SO_4^{2-}$) as the electrolyte.
- Electrodes are made of porous lead (Pb, anode, electrically negative) and porous lead oxide (PbO_2, Cathode, electrically positive).
- Process taking place during discharging is shown in Fig 4a. Where lead is consumed an lead sulfate is formed.
- $\boldsymbol{Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-}$ →4

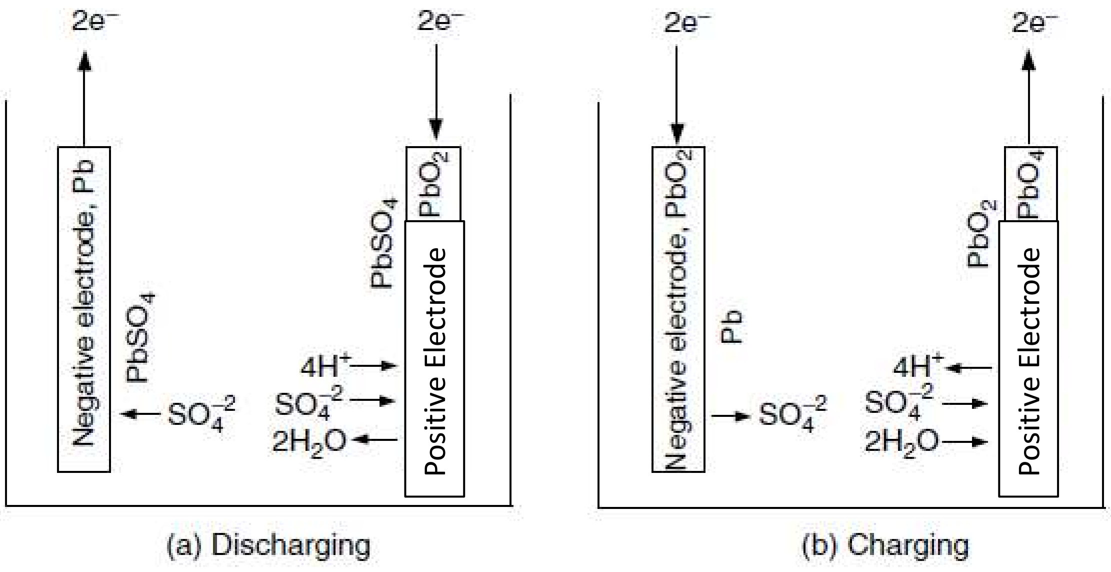


Fig4. Electrochemical processes during the discharge a charge of a lead-acid battery cell

Electrochemical Reactions: Discharging Process

- In Discharge process lead is consumed and lead sulfate is formed. Chemical reaction on the anode is

$$Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^- \rightarrow 4$$

This reaction releases two electrons and thereby, gives rise to an excess negative charge on the electrode that is relieved by a flow of electrons through the external circuit to the positive (cathode) electrode.

At the positive electrode, the lead of PbO_2 is also converted into $PbSO_4$ and at the same time, water is formed.

$$PbO_2 + 4H^+ + SO_4^{2-} + 2e^- \rightarrow PbSO_4 + 2H_2O \rightarrow 5$$

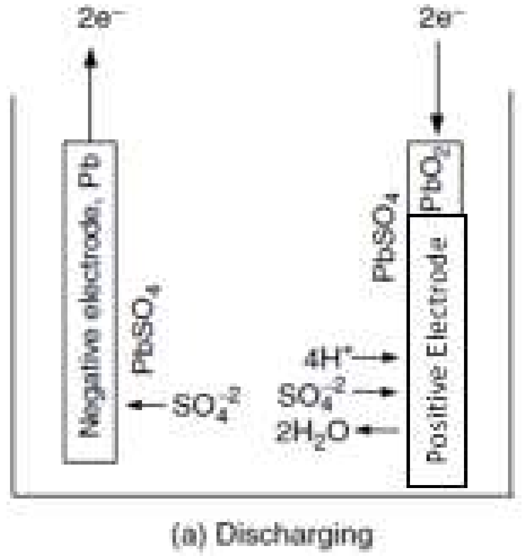


Fig4. Electrochemical processes during the discharge and charge of a lead-acid battery cell

Electrochemical Reactions: Discharging Process

During charging, the reactions on the anode and cathode are reversed as shown in Fig. 4(b) that can be expressed by:

Anode: $PbSO_4 + 2e^- \rightarrow Pb + SO_4^{2-}$ → 6

And

Cathode:

$PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e^-$ → 7

The overall reaction in a lead-acid battery cell can be expressed as

$$Pb + PbO_2 + 2H_2SO_4 \underset{\text{Charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O \quad \rightarrow 8$$

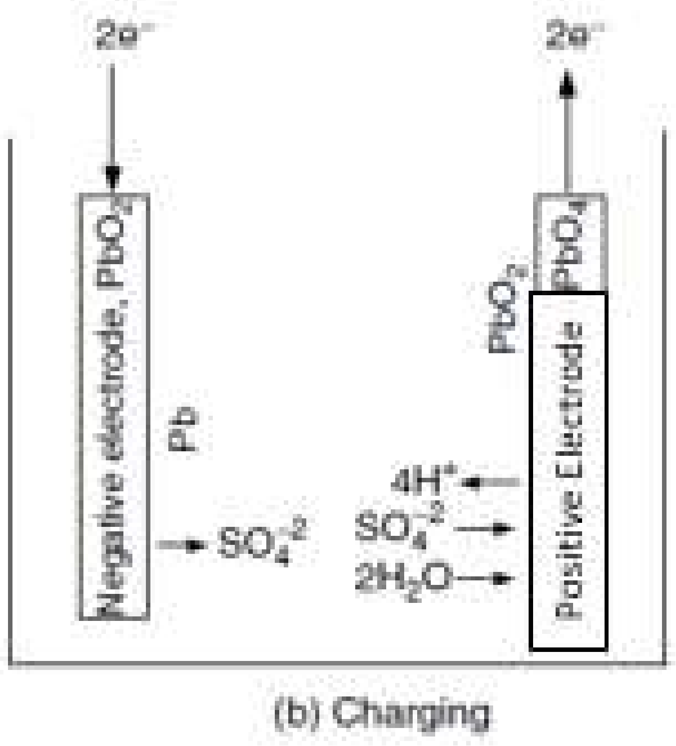
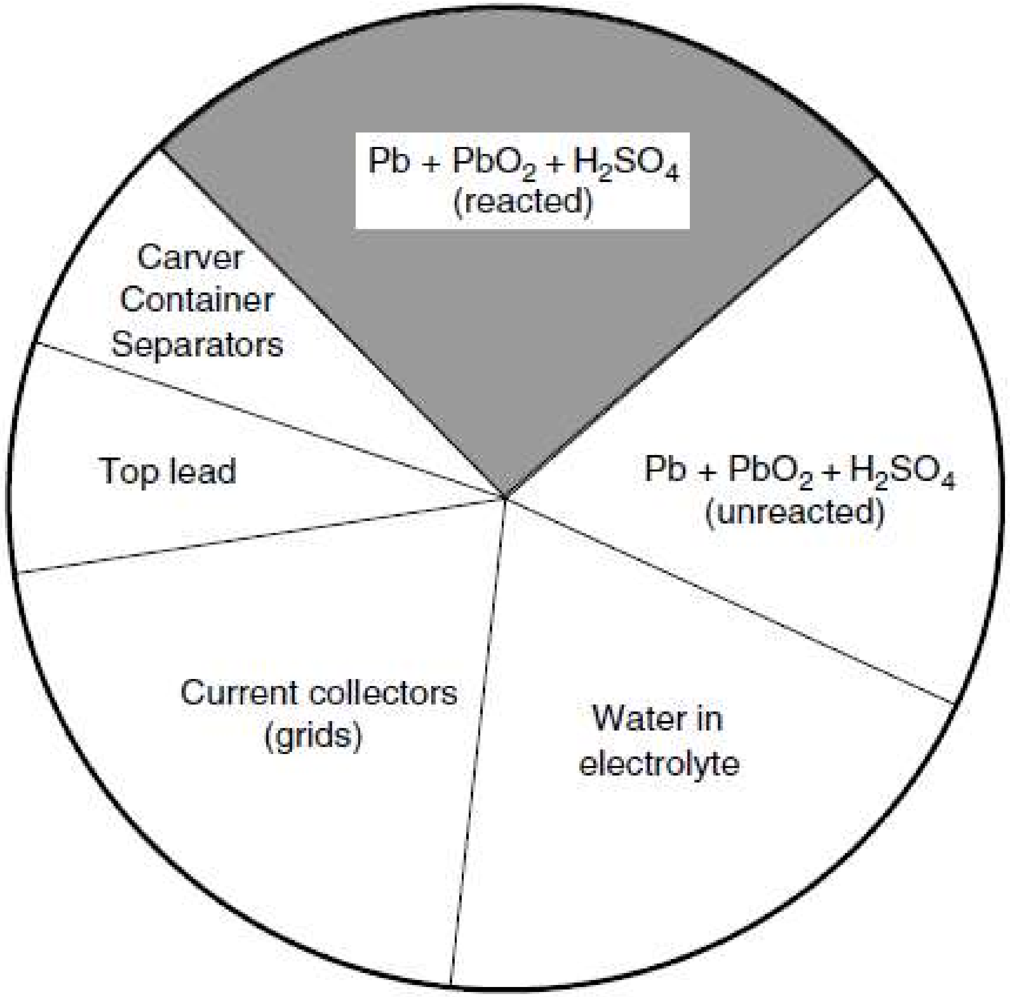


Fig4. Electrochemical processes during the discharge and charge of a lead-acid battery cell

The lead-acid battery has a cell voltage of about 2.03 V at standard condition, which is affected by the concentration of the electrolyte.

Weight distribution of the components of a lead-acid EV battery with a specific energy of 45 Wh/kg at the C5/5 rate



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

Energy Efficiency

- The energy or power losses during battery discharging and charging appear in the form of voltage loss.
- Thus, the efficiency of the battery during discharging and charging can be defined at any operating point as the ratio of the cell operating voltage to the thermodynamic voltage, that is:

During Discharging: $\eta = \frac{V}{V_o}$

And during Charging: $\eta = \frac{V_o}{V}$

- The terminal voltage, as a function of battery current and energy stored in it or SOC, is lower in discharging and higher in charging than the electrical potential produced by a chemical reaction.

- Advanced lead-acid batteries have been developed to remedy these disadvantages.
- The specific energy has been increased through the reduction of inactive materials such as the casing, current collector, separators, etc.
- The lifetime has been increased by over 50% — at the expense of cost, however. The safety issue has been addressed and improved, with electrochemical processes designed to absorb the parasitic releases of hydrogen and oxygen.

Nickel-based Batteries

- Nickel is a lighter metal than lead and has very good electrochemical properties desirable for battery applications.
- There are four different nickel-based battery technologies:
  - Nickel–iron
  - Nickel–zinc
  - Nickel–cadmium, And
  - Nickel–metal Hydride.
- ***Electrolyte: Alkaline aqueous solution***

Positive Electrode	Negative Electrode	Charge reaction	Discharge reaction
NiOOH	Cd	$2NiOOH + 2H_2O + Cd$	$2Ni(OH)_2 + Cd(OH)_2$
NiOOH	Fe	$2NiOOH + 2H_2O + Fe$	$2Ni(OH)_2 + Fe(OH)_2$
NiOOH	Zn	$2NiOOH + 2H_2O + Zn$	$2Ni(OH)_2 + Zn(OH)_2$
NiOOH	H2	$2NiOOH + H_2$	$2Ni(OH)_2$

Nickel/Iron System

- Commercialized during the early years of the 20th century.
- Used in fork-lift trucks, mine locomotives, shuttle vehicles, railway locomotives, and motorized hand-trucks.
- **Positive electrode is Nickel (III) hydroxy-oxide (NiOOH)** and **Negative electrode is metallic iron**.
- **Electrolyte: concentrated solution of potassium hydroxide** (240 g/l) containing lithium hydroxide (50 g/l).
- Cell reaction is : $2NiOOH + 2H_2O + Fe \leftarrow \rightarrow 2NI(OH)_2 + Fe(OH)_2$
- Nominal ***open-circuit voltage is 1.37 V.***
- Nickel/iron batteries suffer from gassing, corrosion, and self-discharge problems.
- These problems have been partially or totally solved in prototypes that have yet to reach the market.
- These batteries are complex due to the need to maintain the water level and the safe disposal of the hydrogen and oxygen released during the discharge process. Nickel–iron batteries also suffer from low temperatures, although less than lead-acid batteries.
- Finally, the cost of nickel is significantly higher than that of lead.
- Their greatest advantages are high power density compared with lead-acid batteries, and a capability of withstanding 2000 deep discharges.

Nickel/Cadmium System

- **Positive electrode is Nickel (III) hydroxy-oxide (NiOOH)** and **Negative electrode is metallic cadmium**.
- Cell reaction in previous slide.
- nominal open-circuit voltage is **1.3 V.**
- Performance is similar to nickel/iron
- Advantages:
  - High specific power: over 220 W/kg
  - Long cycle life:(up to 2000 cycles)
  - A high tolerance of electric and mechanical abuse
  - A small voltage drop over a wide range of discharge currents
  - Rapid charge capability (about 40 to 80% in 18 min)
  - Wide operating temperature (40 to 85°C)
  - Low self-discharge rate (0.5% per day)
  - Excellent long-term storage due to negligible corrosion
  - Availability in a variety of size designs.
- Disadvantages:
  - High initial cost
  - Relatively low cell voltage
  - Environmental hazard of cadmium

Nickel/Cadmium System

- The nickel/cadmium battery can be generally divided into two major categories
  - The vented
  - Sealed types.
- The vented type consists of many alternatives.
  - The vented sintered-plate is a more recent development, which has a high specific energy but is more expensive.
  - It is characterized by a flat discharge voltage profile, and superior high current rate and low-temperature performance. As a result, the battery requires no maintenance.
- A sealed nickel/cadmium battery incorporates a specific cell design feature to prevent a build-up of pressure in the cell caused by gassing during overcharge.
- The major manufacturers of the nickel/cadmium battery for EV and HEV are
  - SAFT and VARTA.
  - Recent EVs powered by the nickel/cadmium battery have included the Chrysler TE Van, Citroën AX, Mazda Roadster, Mitsubishi EV, Peugeot 106, and Renault Clio.3,6

Nickel–Metal Hydride (Ni–MH) Battery

- In the market since 1992.
- characteristics are similar to those of the nickel/cadmium battery.
- The principal difference between them is the use of hydrogen, absorbed in a metal hydride, for the active negative electrode material in place of cadmium.
- Because of its superior specific energy when compared to the Ni–Cd and its freedom from toxicity or carcinogenicity, the Ni–MH battery is superseding the Ni–Cd battery.
- The overall reaction in a Ni–MH battery is

$$MH + NiOOH \leftrightarrow M + Ni(OH)_2$$

- When the battery is discharged, the metal hydride in the negative electrode is oxidized to form metal alloy, and nickel oxyhydroxide in the positive electrode is reduced to nickel hydroxide.
- During charging, the reverse reaction occurs.

Nickel–Metal Hydride (Ni–MH) Battery

- Ni–MH battery nominal voltage :1.2 V
- specific energy of 65 Wh/kg and
- specific power of 200 W/kg.
- A key component of the Ni–MH battery is the hydrogen storage metal alloy, which is formulated to obtain a material that is stable over a large number of cycles.
- There are two major types of these metal alloys being used.
    - Rare-earth alloys based around lanthanum nickel, known as AB5
    - Alloys consisting of titanium and zirconium, known as AB2
- The AB2 alloys have a higher capacity than the AB5 alloys.
- However, the trend is to use AB5 alloys because of better charge retention and stability characteristics.

Nickel–Metal Hydride (Ni–MH) Battery

- Advantages based on present technology:
  - It has the highest specific energy (70 to 95 Wh/kg)
  - Highest specific power (200 to 300 W/kg) of nickel-based batteries
  - Environmental friendliness (cadmium free)
  - Flat discharge profile (smaller voltage drop) and
  - Rapid recharge capability.
- However, this battery still suffers from its high initial cost.
- Also, it may have a memory effect and may be exothermic on charge.

- The Ni–MH battery has been considered as an important near-term choice for EV and HEV applications. A number of battery manufacturers, such as GM Ovonic, GP, GS, Panasonic, SAFT, VARTA, and YUASA, have actively engaged in the development of this battery technology, especially for powering EVs and HEVs. Since 1993, Ovonic battery has installed its Ni–MH battery
- in the Solectric GT Force EV for testing and demonstration. A 19-kWh battery has delivered over 65 Wh kg, 134 km/h, acceleration from zero to 80 km/h in 14 sec, and a city driving range of 206 km. Toyota and Honda have used the Ni–MH battery in their HEVs — Prius and Insight, respectively

Lithium-Based Batteries

- Lithium is the lightest of all metals and presents very interesting characteristics from an electrochemical point of view.
- Indeed, it allows a very high thermodynamic voltage, which results in a very high specific energy and specific power.
- There are two major technologies of lithium-based batteries:
  - lithium–polymer and
  - lithium-ion.

Lithium–Polymer (Li–P) Battery

- Lithium–polymer batteries use lithium metal and a transition metal intercalation oxide (M*y*O*z*) for the negative and positive electrodes, respectively.
- This M*y*O*z* possesses a layered structure into which lithium ions can be inserted, or from where they can be removed on discharge and charge, respectively. A thin solid polymer electrolyte (SPE) is used, which offers the merits of improved safety and flexibility in design.
- The general electrochemical reactions are $xLi + M_yO_z <-> Li_xM_y O_z$
- On discharge, lithium ions formed at the negative electrode migrate throughthe SPE, and are inserted into the crystal structure at the positive electrode.
- On charge, the process is reversed. By using a lithium foil negative electrode and vanadium oxide (V6O13) positive electrode, the Li/SPE/V6O13 cell is the most attractive one within the family of Li–polymer.
  - It operates at a nominal voltage of 3 V
  - Specific energy of 155 Wh/kg
  - Specific power of 315 W/kg.
- The corresponding advantages are a very low self-discharge rate (about 0.5% per month), capability of fabrication in a variety of shapes and sizes, and safe design (reduced activity of lithium with solid electrolyte).
- However, it has the drawback of a relatively weak low-temperature performance due to the temperature dependence of ionic conductivity.

Lithium-Ion (Li-Ion) Battery

- Since the first announcement of the Li-ion battery in 1991, Li-ion battery technology has seen an unprecedented rise to what is now considered to be the most promising rechargeable battery of the future. Although still at the development stage, the Li-ion battery has already gained acceptance for EV and HEV applications.
- The Li-ion battery uses a lithiated carbon intercalation material ($LixC$) for the negative electrode instead of metallic lithium, a lithiated transition metal intercalation oxide ($Li1x\ MyOz$) for the positive electrode, and a liquid organic solution or a solid polymer for the electrolyte. Lithium ions
- swing through the electrolyte between the positive and negative electrodes during discharge and charge. The general electrochemical reaction is described as
- $LixCLi1xMyOz \leftrightarrow CLiMyOz$

Lithium-Ion (Li-Ion) Battery

- On discharge, lithium ions are released from the negative electrode, migrate via the electrolyte, and are taken up by the positive electrode. On charge, the process is reversed. Possible positive electrode materials include Li1*x*CoO2, Li1*x*NiO2, and Li1*x*Mn2O4, which have the advantages of stability in air, high voltage, and reversibility for the lithium intercalation reaction.
- The Li*x*C/Li1*x*NiO2 type, loosely written as C/LiNiO2 or simply called the nickel-based Li-ion battery, has a nominal voltage of 4 V, a specific energy of 120 Wh/kg, an energy density of 200 Wh/l, and a specific power of 260 W/kg.
- The cobalt-based type has a higher specific energy and energy density, but at a higher cost and significant increase in the self-discharge rate.
- The manganese-based type has the lowest cost and its specific energy and energy density lie between those of the cobalt- and nickel-based types.
- It is anticipated that the development of the Li-ion battery will ultimately move to the manganese-based type because of the low cost, abundance, and environmental friendliness of the manganese-based materials.

Lithium-Ion (Li-Ion) Battery

- Many battery manufacturers,
- SAFT, GS Hitachi, Panasonic, SONY, and VARTA, have actively engaged in the development of the Li-ion battery.
- Starting in 1993, SAFT focused on the nickel-based Li-ion battery.
- Recently, SAFT reported the development of Li-ion high-power batteries for HEV applications with a specific energy of 85 Wh/kg and a specific power of 1350 W/kg.
- They also announced high-energy batteries for EV applications with about 150 Wh/kg and 420 W/kg (at 80% SOC, 150 A current, and 30 sec), respectively

Ragone plot

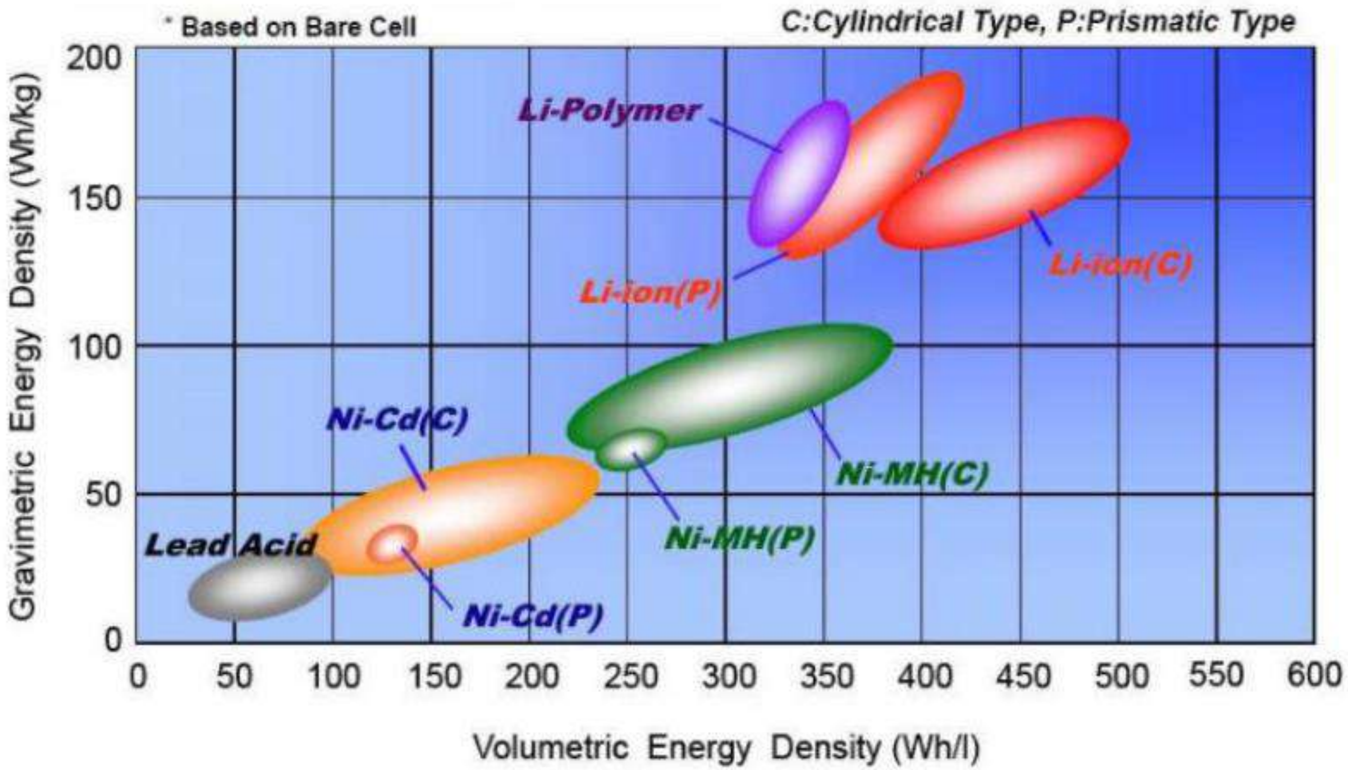
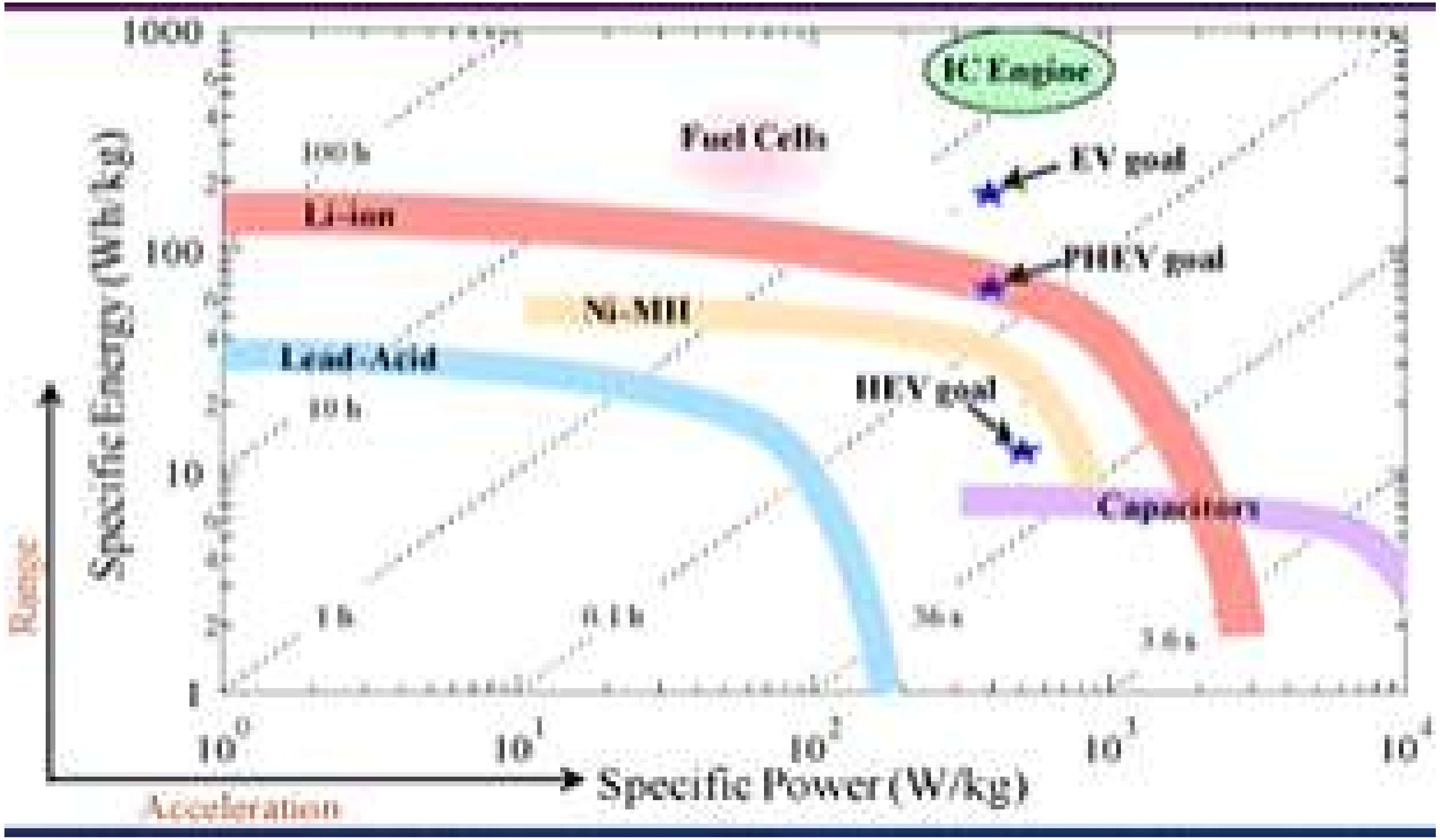


Photo Credit: NASA - National Aeronautics and Space Administration

Batteries comparision:

- https://www.omazaki.co.id/en/electric-car-batteries-and-their-characteristics/



1000
100
10
1
IC Engine
Fuel Cells
EV goal
PHEV goal
HEV goal
Li-ion
Ni-MH
Lead-Acid
Capacitors
100 h
10 h
1 h
0.1 h
36 s
3.6 s
Specific Energy (Wh/kg)
Range
Specific Power (W/kg)
Acceleration
10^0
10^1
10^2
10^3
10^4

Ultracapacitors

- Because of the frequent stop/go operation of EVs and HEVs, the discharging and charging profile of the energy storage is highly varied.
- The average power required from the energy storage is much lower than the peak power of relatively short duration required for acceleration and hill climbing.
- The ratio of the peak power to the average power can be over 10:1 (Chapter 2).
- In fact, the energy involved in the acceleration and deceleration transients is roughly two thirds of the total amount of energy over the entire vehicle mission in urban driving (Chapters 8 and 9).
- In HEV design, the peak power capacity of the energy storage is more important than its energy capacity, and usually constrains its size reduction.

Ultracapacitors

- Based on present battery technology, battery design has to carry out the trade-off among the specific energy and specific power and cycle life.
- The difficulty in simultaneously obtaining high values of specific energy, specific power, and cycle life has led to some suggestions that the energy storage system of EV and HEV should be a hybridization of an energy source and a power source.
- The energy source, mainly batteries and fuel cells, has high specific energy whereas the power source has high specific power.
- The power sources can be recharged from the energy source during less demanding driving or regenerative braking. The power source that has received wide attention is the ultracapacitor.

Features of Ultracapacitors

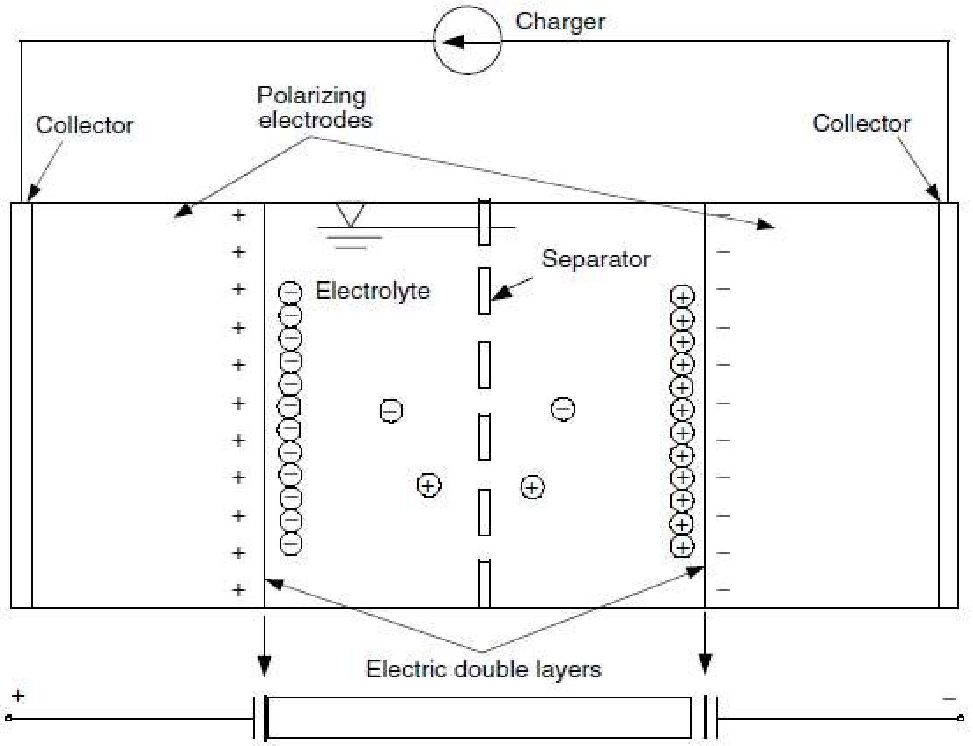
- The ultracapacitor is characterized by much higher specific power, but much lower specific energy compared to the chemical batteries.
- Its specific energy is in the range of a few watt-hours per kilogram.
- However, its specific power can reach up to 3 kW/kg, much higher than any type of battery.
- Due to their low specific energy density and the dependence of voltage on the SOC, it is difficult to use ultracapacitors alone as an energy storage for EVs and HEVs.
- Nevertheless, there are a number of advantages that can result from using the ultracapacitor as an auxiliary power source.

Features of Ultracapacitors

- One promising application is the so-called battery and ultracapacitor hybrid energy storage system for EVs and HEVs.
- Specific energy and specific power requirements can be decoupled, thus affording an opportunity to design a battery that is optimized for the specific energy and cycle life with little attention being paid to the specific power.
- Due to the load leveling effect of the ultracapacitor, the high-current discharging from the battery and the high-current charging to the battery by regenerative braking is minimized so that the available energy, endurance, and life of the battery can be significantly increased.

Basic Principles of Ultracapacitors

- Double-layer capacitor technology is the major approach to achieve the ultracapacitor concept. And the basic principle is as shown in fig.
- Two carbon rods are immersed in a thin sulfuric acid solution. Each rod is separated with each other and charged with voltage increasing from 0 to 1.5V.
- No change occurs up to 1V. At 1.2V, a small bubble appears in the surface of the electrodes. Those bubbles indicate electrical decomposition of water.
- Current does not flow below the decomposition voltage. And an electric double layer then occurs at the boundary of electrode and electrolyte. The electrons are charged across the double layer and for the capacitor.
- An electrical double layer works as an insulator only below the decomposing voltage.



Basic Principles of Ultracapacitors

- The stored energy $E_{cap} = \frac{1}{2} CV^2$
  - Where C is Capacitance in Farads
  - V is the usable voltage in volts.
- As per the equation, higher the voltage, larger the energy density capacitors.
- So, capacitors rated voltage with an aqueous electrolyte is 0.9V per cell. With nonaqueous electrolyte it is 2.3 to 3.3 V per each cell.
- Usage of electric double layer in place of plastic or aluminum films in a capacitor is more advantageous. As the double layer is very thin (as thin as one molecule with no pin holes) and the capacity per area is quite large at 2.5 to 5 μF/ cm^2.

Basic Principles of Ultracapacitors

- Even if a few μF/ cm^2 are obtainable, the energy density of capacitors is not large when using aluminum foil.
- For increasing capacitance, electrodes are made from specific materials that have a very large area, such as activated carbons, which are famous for their surface areas of 1,000 to 3,000 m^2 /g.
- To those surfaces, ions are adsorbed and result in 50 F/g

(1,000 m^2 /g x 5 F/c m^2 x 10,000 c m^2 / m^2 = 50 F/g).

- Assuming that the same weight of electrolyte is added, 25 F/g is quite a large capacity density.
- Nevertheless, the energy density of these capacitors is far smaller than secondary batteries; the typical specific energy of ultracapacitors at present is about 2 Wh/kg, ie., only 1/20 of 40 Wh/kg, which is the available value of typical lead-acid batteries.

Performance of Ultracapacitors

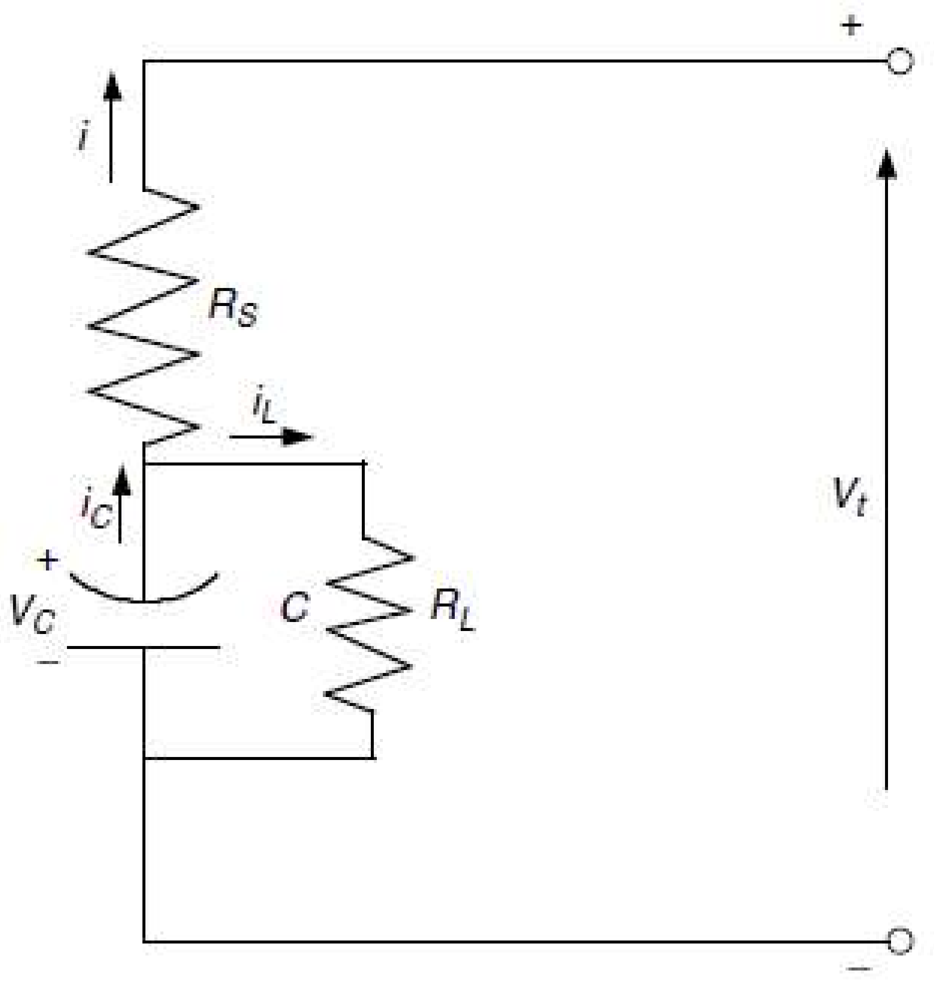
- The performance of an ultracapacitor may be represented by terminal voltages during discharge and charge with different current rates.
- There are three parameters in a capacitor:
  - The capacitance itself (its electric potential V_c),
  - The series resistance R_s, and
  - The dielectric leakage resistance, R_L.
- The terminal voltage of the ultracapacitor during discharge can be expressed as

$$V_t = V_c - i\,R_s \rightarrow 1$$

Electric potential of a capacitor can be expressed by

$$\frac{dV_c}{dt} = -\left(\frac{i+i_L}{C}\right) \rightarrow 2$$

i_L is the leakage current where $i_L = \frac{V_c}{R_L} \rightarrow 3$



C is the capacitance of the ultracapacitor

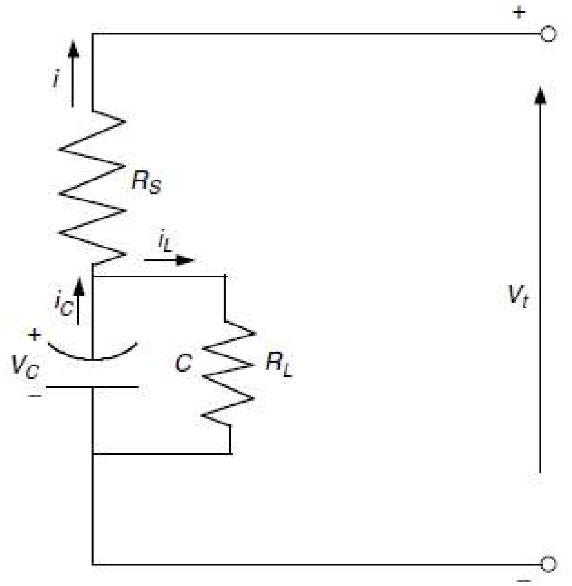
Performance of Ultracapacitors

Substituting equation 3in equation 2,

$$\frac{dV_c}{dt} = \frac{V_c}{CR_L} - \left(\frac{i}{C}\right).$$

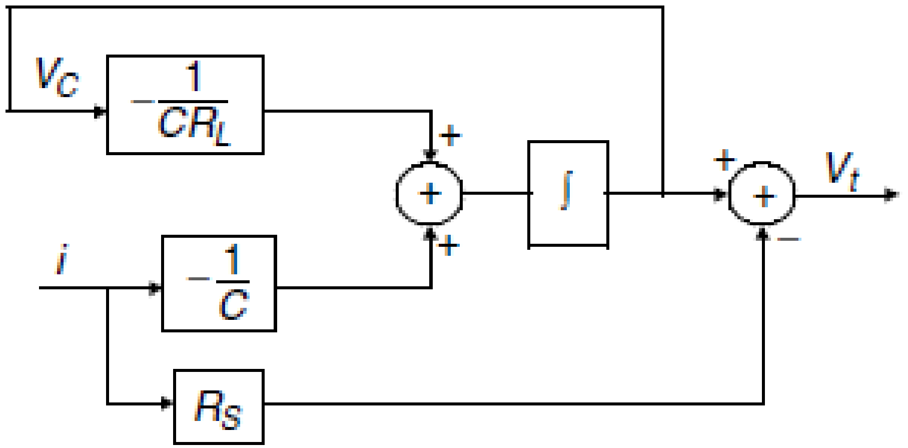
Therefore $V_c = \left[V_{co} \int_0^t \frac{i}{C}\, e^{t/CR_L} dt\right] e^{t/CR_L}$

where i is the discharge current, which is a function of time in real operation.



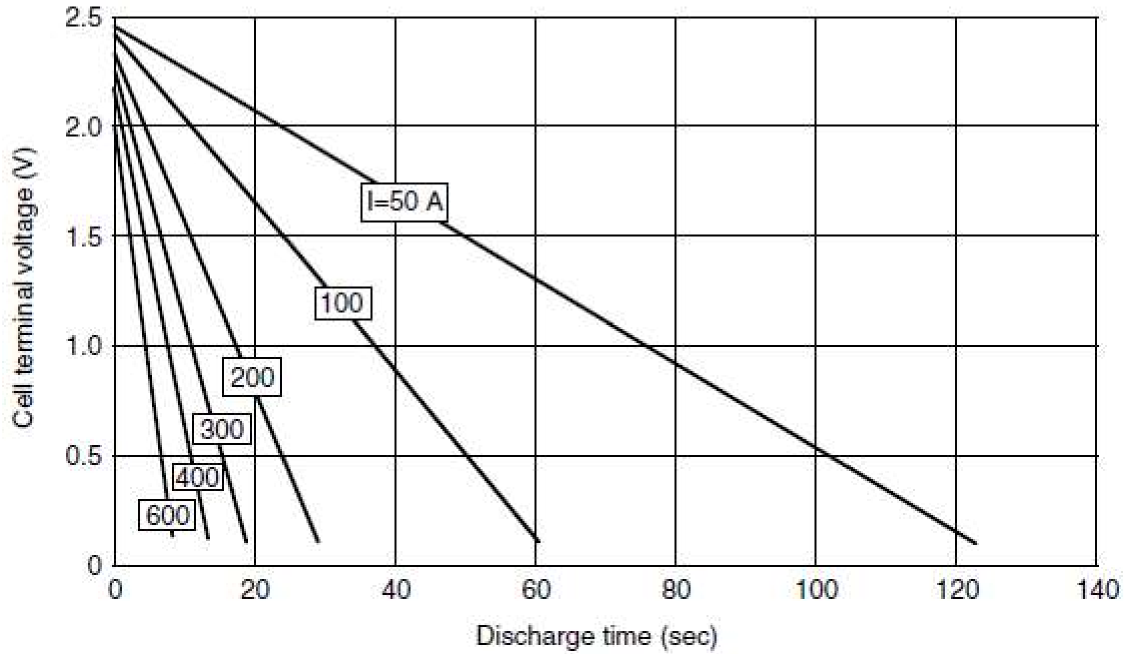
Block Diagram of the Ultracapacitor model

$$V_c = \left[V_{co} \int_0^t \frac{i}{C}\, e^{t/CR_L} dt\right] e^{t/CR_L}$$



Performance of Ultracapacitors

- At different discharge current rates, voltage decreases linearly with discharge time.
- At a large discharge current rate, the voltage decreases much faster than at a small current rate.



Performance of Ultracapacitors

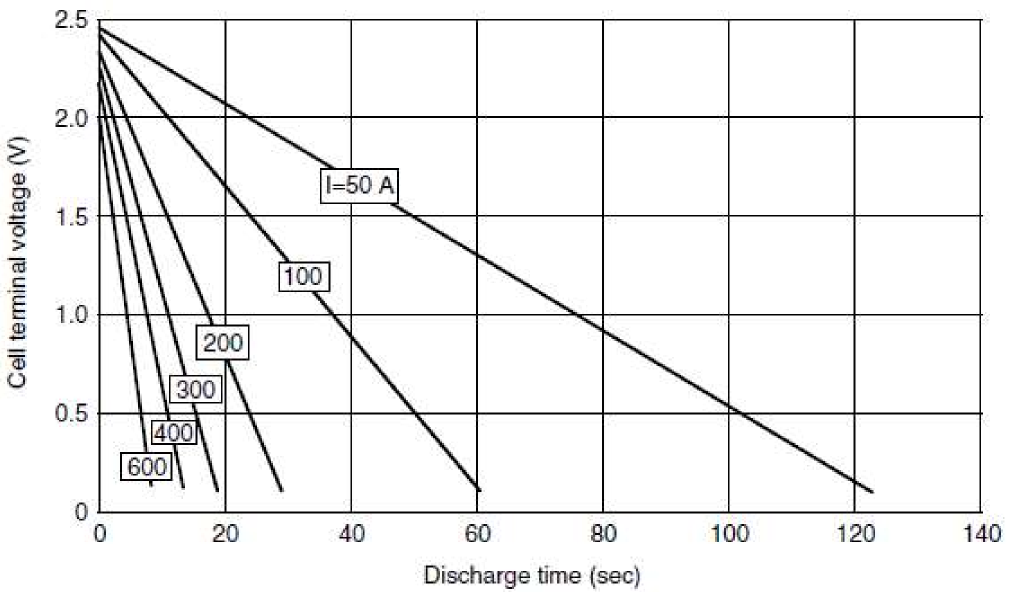
- Operation efficiency in discharging and charging can expressed as

Discharging:

$$\eta_d = \frac{V_t I_t}{V_C I_C} = \frac{(V_C - I_t R_s) I_t}{V_C (I_t + I_L)}$$

And

Charging: $$\eta_c = \frac{V_c I_c}{V_t I_t} = \frac{V_C (I_t - I_L)}{(V_C + I_t R_s) I_t}$$



In actual operation, I_L is very small and can be ignored. Thus,

$$\eta_d = \frac{V_t I_t}{V_C I_C} = \frac{(V_C - I_t R_s)}{V_C} = \frac{V_t}{V_C}$$

And Charging: $$\eta_c = \frac{V_C}{V_C + R_s I_t} = \frac{V_c I_c}{V_t I_t}$$

Ultracapacitor Technologies

- According to the goals set by the U.S. Department of Energy for the inclusion of ultracapacitors in EVs and HEVs, the near-term specific energy and specific power should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kg and 1600 W/kg.
- So far, none of the available ultracapacitors can fully satisfy these goals.
- Nevertheless, some companies are actively engaged in the research and development of ultracapacitors for EV and EHV applications.
- Maxwell Technologies has claimed that its power BOOSTCAP ultracapacitor cells (2600 F at 2.5 V) and integrated modules (145 F at 42 V and 435 F at 14 V) are in production.
- The technical specifications are listed in Table 10.3.

Ultracapacitor Technologies

Technical Specifications of the Maxwell Technologies Ultracapacitor Cell and Integrated Modules[5]

	BCAP0010 (Cell)	BMOD0115 (Module)	BMOD0117 (Module)
Capacitance (farads, −20%/+20%)	2600	145	435
maximum series resistance ESR at 25°C (mΩ)	0.7	10	4
Voltage (V), continuous (peak)	2.5 (2.8)	42 (50)	14 (17)
Specific power at rated voltage (W/kg)	4300	2900	1900
Specific energy at rated voltage (Wh/kg)	4.3	2.22	1.82
Maximum current (A)	600	600	600
Dimensions (mm) (reference only)	60 × 172 (Cylinder)	195 × 165 × 415 (Box)	195 × 265 × 145 (Box)
Weight (kg)	0.525	16	6.5
Volume (l)	0.42	22	7.5
Operating temperature[a] (°C)	−35 to +65	−35 to +65	−35 to +65
Storage temperature (°C)	−35 to +65	−35 to +65	−35 to +65
Leakage current (mA) 12 h, 25°C	5	10	10

Ultrahigh-Speed Flywheels

- The use of flywheels for storing energy in mechanical form is not a new concept.
- More than 25 years ago, the Oerlikon Engineering Company in Switzerland made the first passenger bus solely powered by a massive flywheel.
- This flywheel, which weighed 1500 kg and operated at 3000 rpm, was recharged by electricity at each bus stop.
- The traditional flywheel is a massive steel rotor with hundreds of kilograms that spins on the order of ten hundreds of rpm.
- On the contrary, the advanced flywheel is a lightweight composite rotor with tens of kilograms and rotates on the order of 10,000 rpm; it is the so-called ultrahigh-speed flywheel.
- The concept of ultrahigh-speed flywheels appears to be a feasible means for fulfilling the stringent energy storage requirements for EV and HEV applications, namely high specific energy, high specific power, long cycle life, high-energy efficiency, quick recharge, maintenance free characteristics, cost effectiveness, and environmental friendliness.

Operation Principles of Flywheels

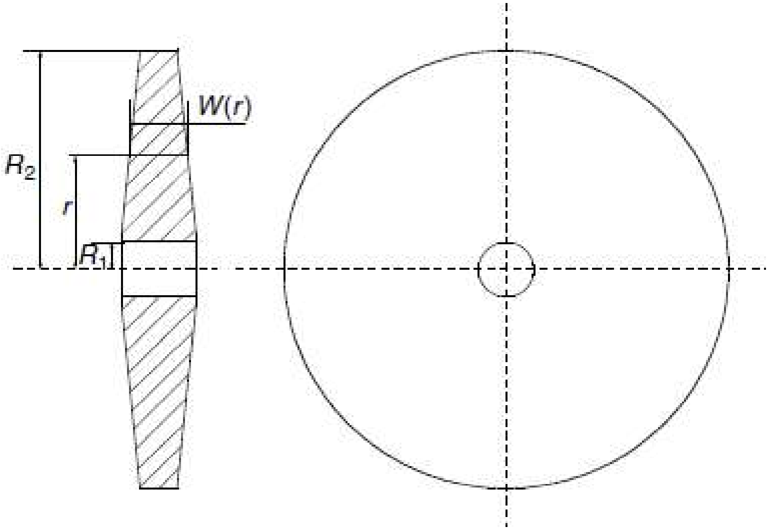
- A rotating flywheel stores energy in the kinetic form as $E_f = \frac{1}{2} J_f \omega_f^2$

J_f → Moment of inertia of the flywheel in kgm^2/sec

and ω_f is the angular velocity of the flywheel in rad/sec.

It indicates that the energy stored in a flywheel is proportional to the moment of inertia of the flywheel and flywheel rotating speed squared.

- A lightweight flywheel should be designed to achieve moment of inertia per unit mass and per unit volume by properly designing its geometric shape.



Geometry of a typical flywheel

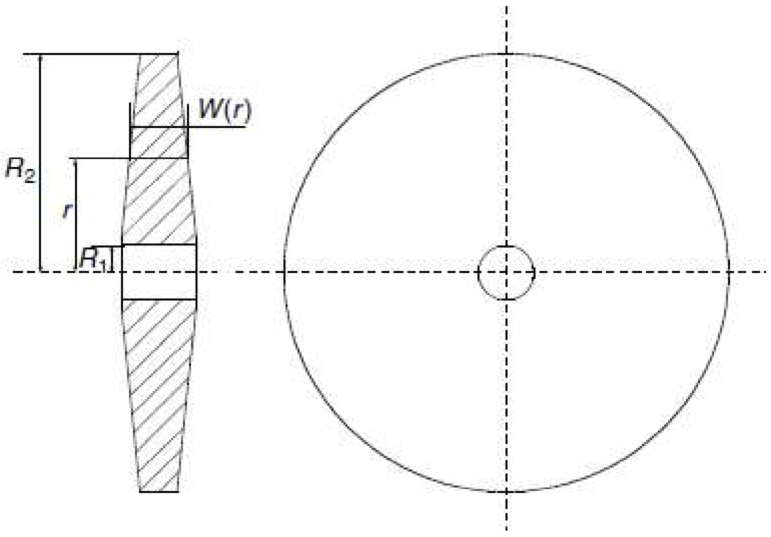
Operation Principles of Flywheels

- The moment of inertia of a flywheel can be calculated by
  $J_f = 2\pi\rho \int_{R_1}^{R_2} W(r) r^3 dr$
- where ρ is the material mass density and *W*(*r*) is the width of the flywheel corresponding to the radius *r*, as shown in Fig.
- The mass of the flywheel can be calculated by

$$M_f = 2\pi\rho \int_{R_1}^{R_2} W(r) r dr$$

Thus, the specific moment of inertia of a flywheel is defined as the moment of inertia per unit mass, expressed as

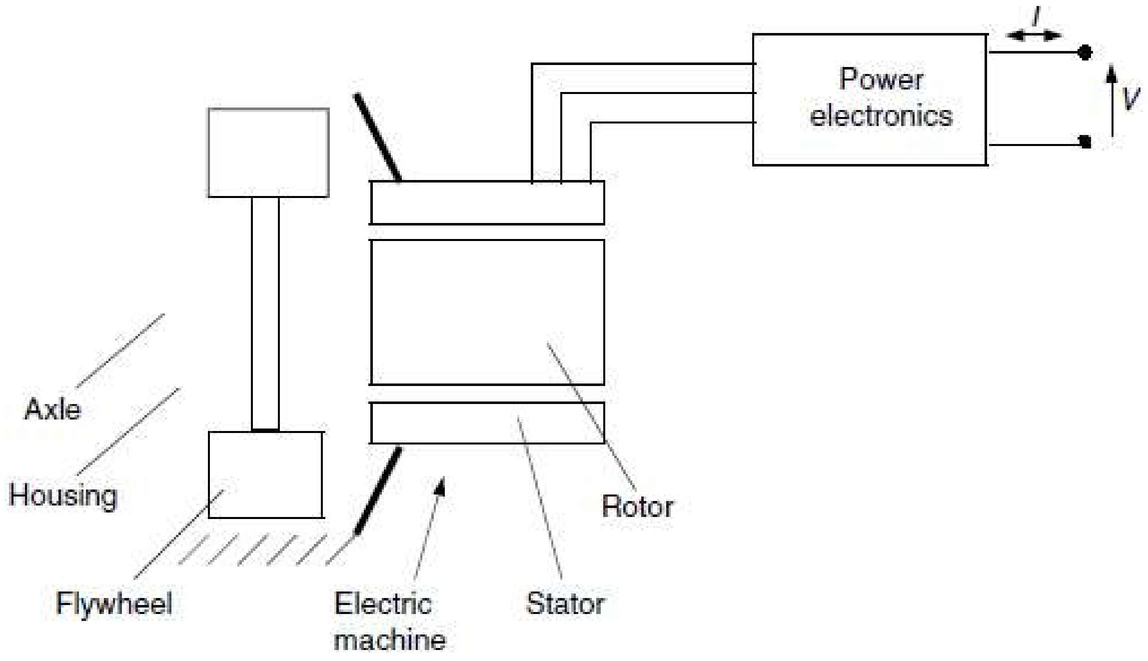
$$J_{fs} = \frac{\int_{R_1}^{R_2} W(r) r^3 dr}{\int_{R_1}^{R_2} W(r) r dr}$$



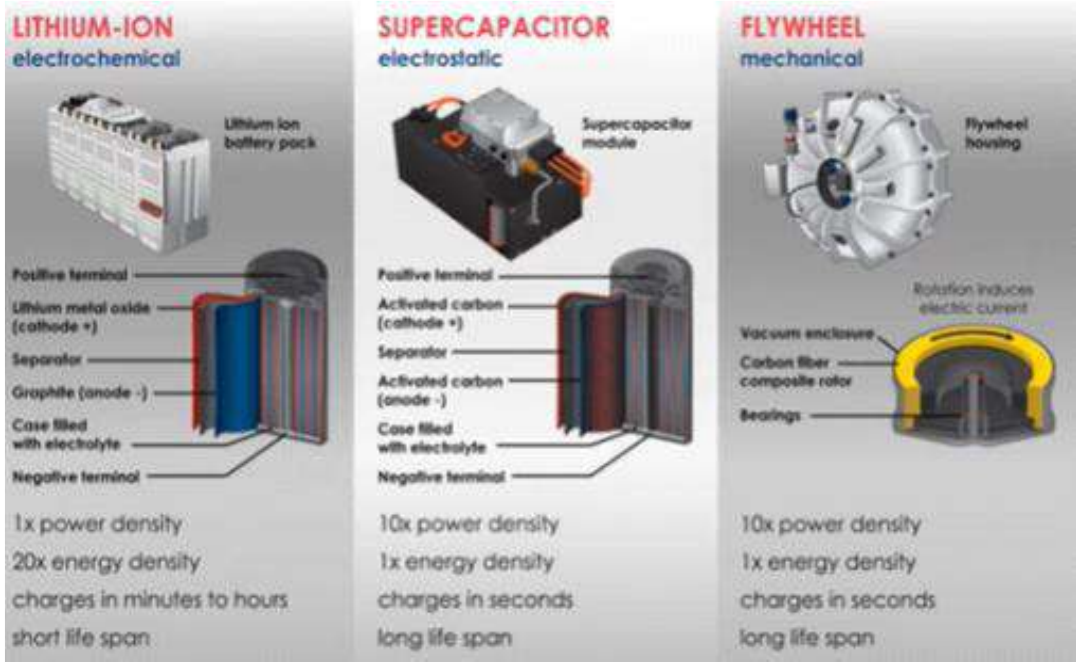
Geometry of a typical flywheel

Operation Principles of Flywheels

- At present, a speed of over 60,000 rpm has been achieved in some prototypes.
- With current technology, it is difficult to directly use the mechanical energy stored in a flywheel to propel a vehicle, due to the need for continuous variation transmission (CVT) with a wide gear ratio variation range.
- The commonly used approach is to couple an electric machine to the flywheel directly or through a transmission to constitute a mechanical battery.
- The electric machine, functioning as the energy input and output port, converts the mechanical energy into electric energy or vice versa.

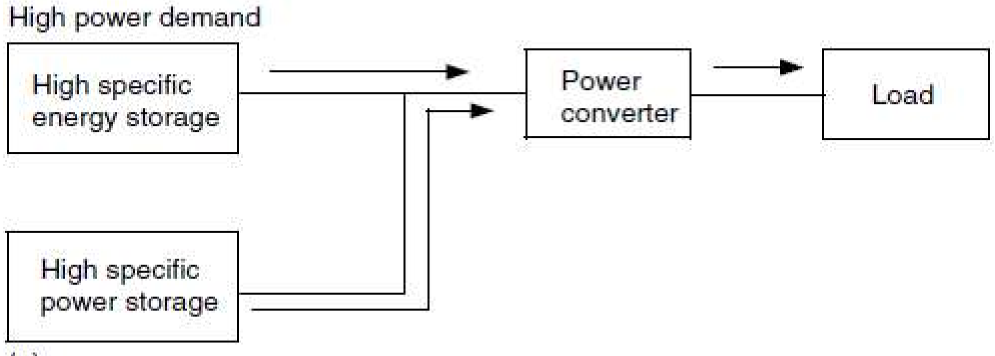


Comparison of energy sources



Hybridization of Energy Storages

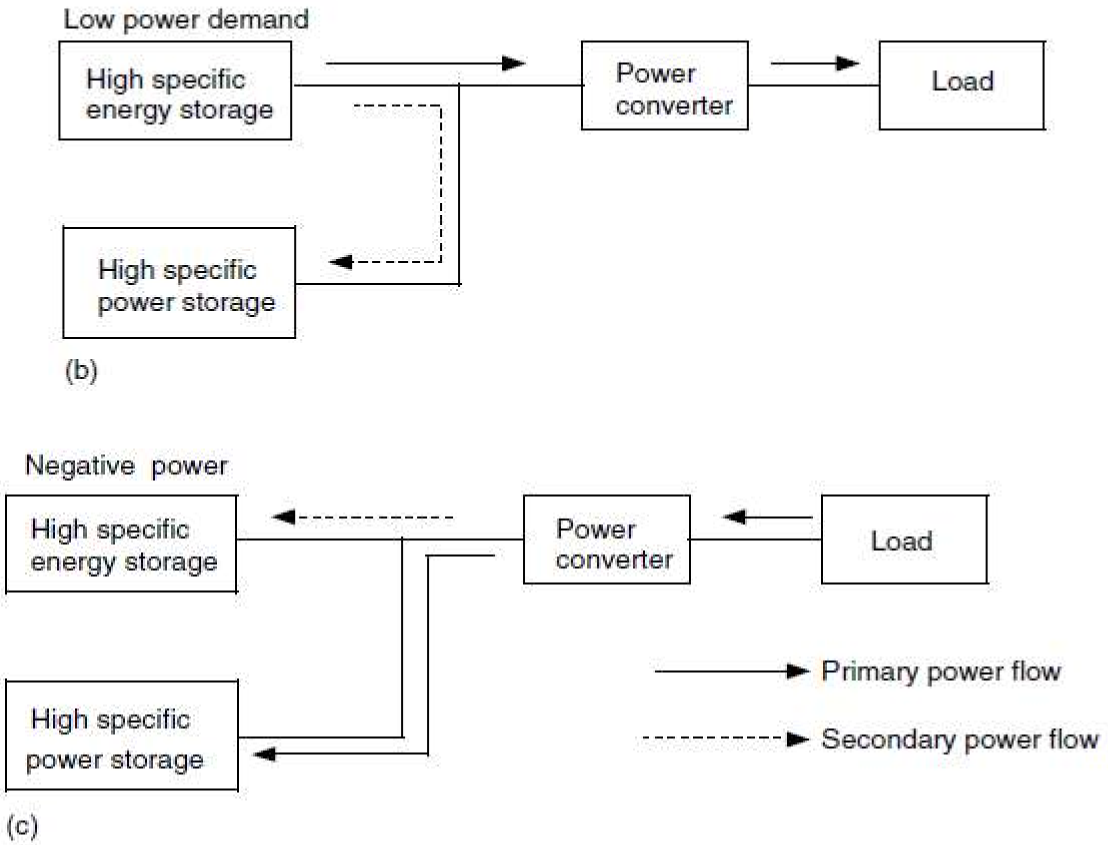
- The hybridization of energy storage is to combine two or more energy storages together so that the advantages of each one can be brought out and the disadvantages can be compensated by others.
- For instance, the hybridization of a chemical battery with an ultracapacitor can overcome such problems as low specific power of electrochemical batteries and low specific energy of ultracapacitors, therefore achieving high specific energy and high specific power.
- Basically, the hybridized energy storage consists of two basic energy storages:
- one with high specific energy and the other with high specific power.
- In high power demand operations, such as acceleration and hill climbing, both basic energy storages deliver their power to the load as shown in Figure (a).



(a)

Hybridization of Energy Storages

- On the other hand, in low power demand operation, such as constant speed cruising operations, the high specific energy storage will deliver its power to the load and charge the high specific power storage to recover its charge lost during high power demand operation, as shown in Figure 10.18(b).
- In regenerative braking operations, the peak power will be absorbed by the high specific power storage, and only a limited part is absorbed by the high specific energy storage.
- In this way, the whole system would be much smaller in weight and size than if any one of them alone was the energy storage.
- Based on the available technologies of various energy storages, there are several viable hybridization schemes for EVs and HEVs, typically, battery and battery hybrids, and battery and ultracapacitor hybrids. The latter is more natural since the ultracapacitor can offer much higher power than batteries, and it collaborates with various batteries to form the battery and ultracapacitor hybrids.



Hybridization of Energy Storages

- During hybridization, the simplest way is to connect the ultracapacitors to the batteries directly and in parallel, as shown in fig. a
- In this configuration, the ultracapacitors simply act as a current filter, which can significantly level the peak current of the batteries and reduce the battery voltage drop as shown in Figure b.
- The major disadvantages of this configuration are that the power flow cannot be actively controlled and the ultracapacitor energy cannot be fully used.

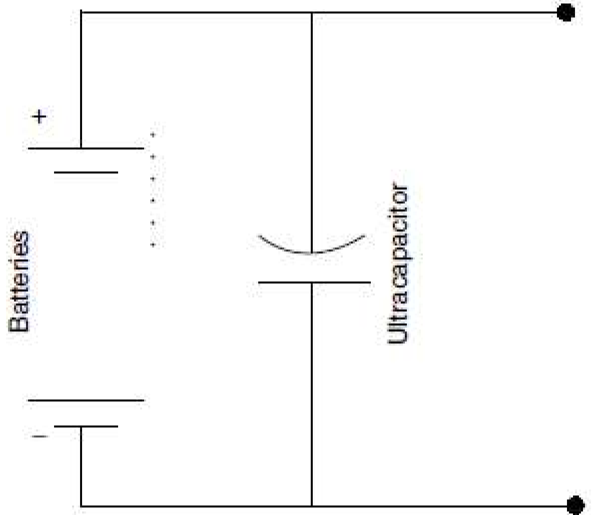


Fig a. Direct and parallel connection of batteries and ultracapacitors

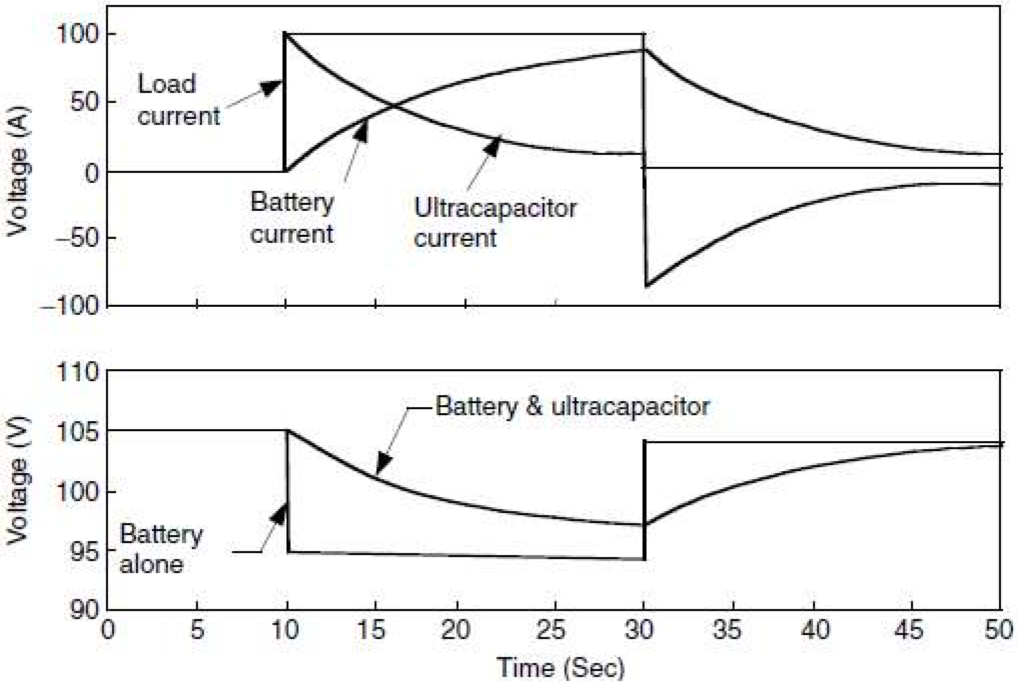


Fig b. Variation of battery and ultracapacitor currents and voltages with a step current output change

Hybridization of Energy Storages

- Figure c shows a configuration in which a two-quadrant DC/DC converter is placed between the batteries and ultracapacitors.
- This design allows batteries and the ultracapacitors to have a different voltage, the power flow between them can be actively controlled, and the energy in the ultracapacitors can be fully used.
- In the long term, an ultrahigh-speed flywheel would replace the batteries in hybrid energy storage to obtain a high efficiency, compact, and long-life storage system for EVs and HEVs

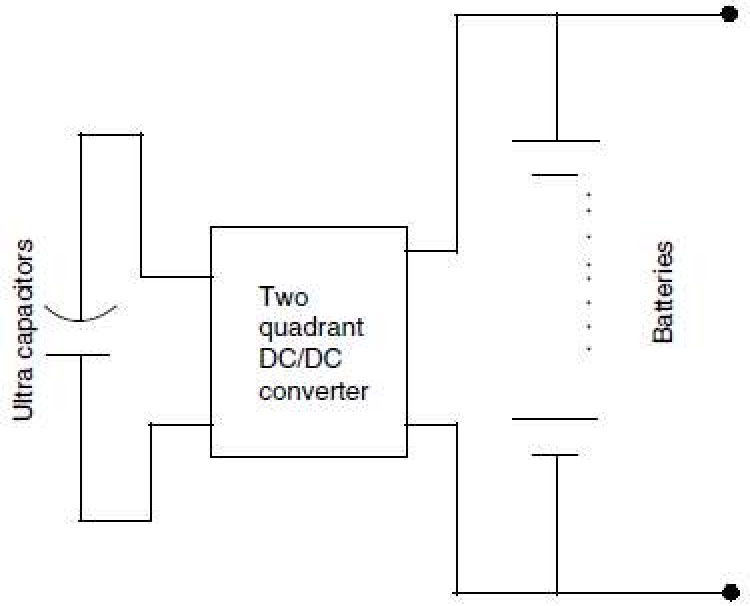


Fig C: Actively controlled hybrid battery/ultracapacitor energy storage

III Year B.Tech. EEE II-Semester

Electric & Hybrid Vehicles
Course Code: PE116CW 3
(Professional Elective-II)

Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

UNIT 2: (~8 Lecture Hours)

- Energy storage:
- **Introduction to energy storage requirements in hybrid and electric vehicles.**
- **Electro chemical batteries and its analysis,**
- Ultra capacitors and its analysis,
- Ultra high speed flywheels and its analysis,
- Hybridization of Energy storages.

Battery pack types

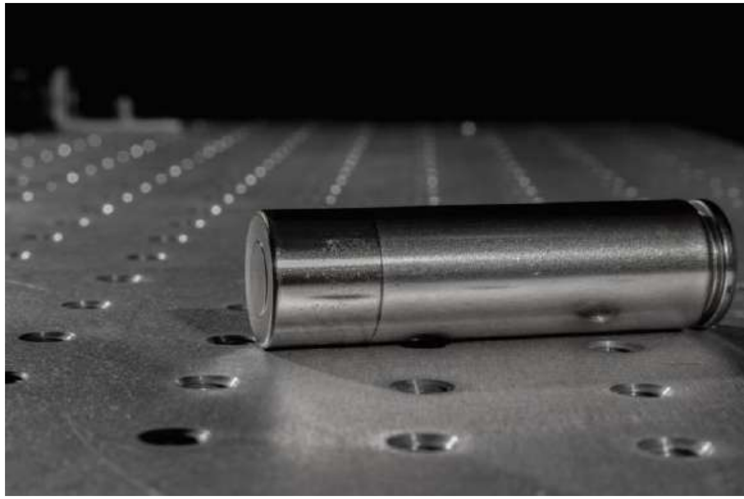
- Primary: Primary batteries are disposable, non-rechargeable devices. They must be replaced once their energy supply is depleted.
- secondary or rechargeable: Secondary or rechargeable batteries contain active materials that can be regenerated.

Electric vehicle battery cell formats

- Cylindrical cells
- Prismatic cells
- Pouch cells
- Coin cells (still under Research , Development and testing but not used in EV)

Cylindrical Cells

- Least expensive to manufacture
- Good mechanical resistance.
- Because of their shape, cylindrical cells have limitations in terms of power. For this reason, EVs with smaller batteries such as hybrid vehicles use pouch or prismatic cells to deliver more power during accelerations.

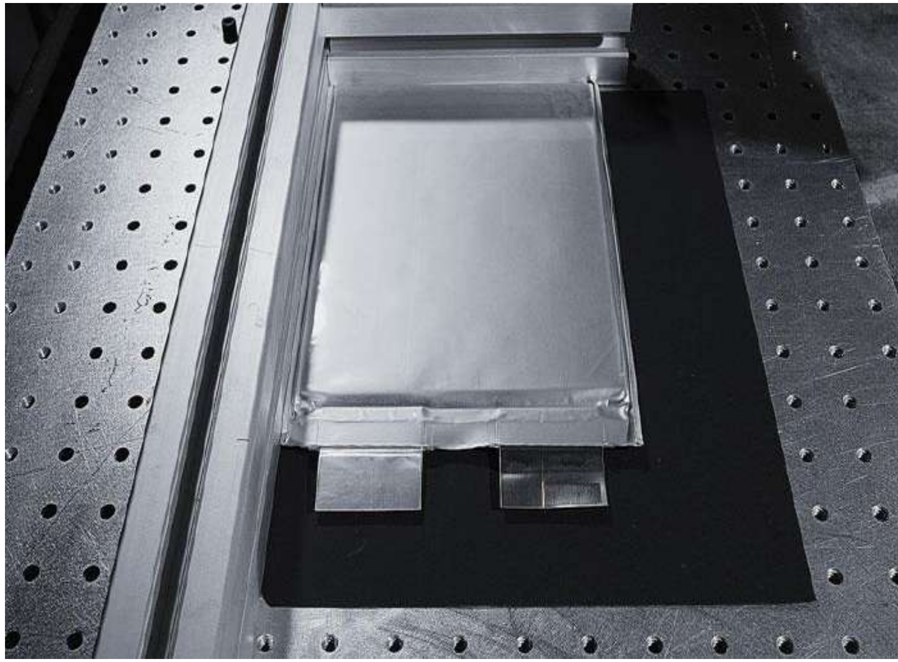


Prismatic Cells

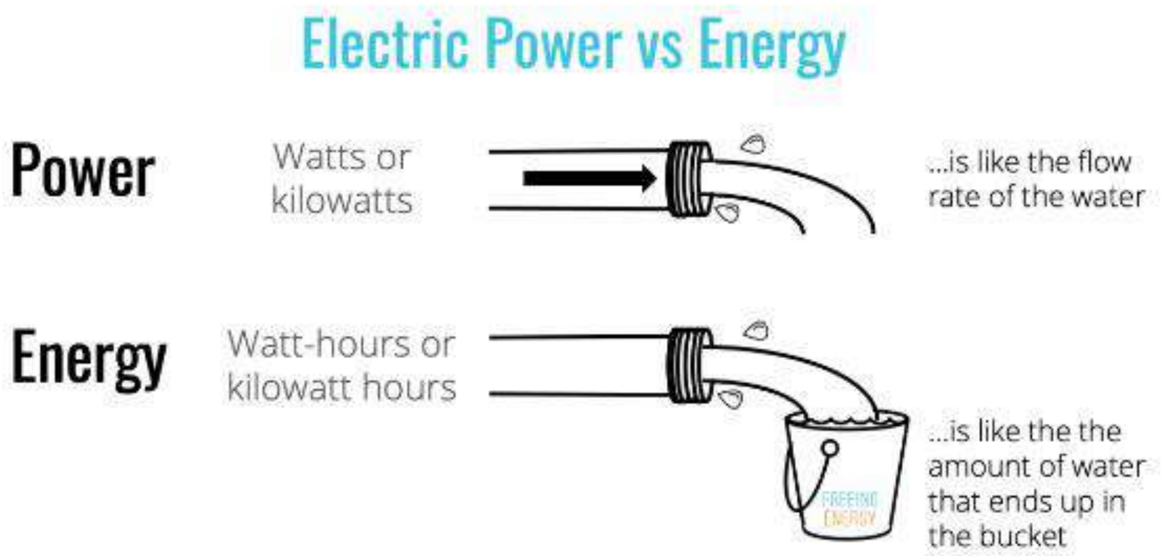
- Prismatic cells can be 20 to 100 times larger than cylindrical cells.
- Typically deliver more power and store more energy for the same volume because less material is used for the casing.
- The casing's shape and thickness also allow better heat management than cylindrical cells.
- Prismatic cells are popular among Chinese manufacturers because their preferred cell chemistry (the lithium iron phosphate battery)
- Prismatic cells are mainly used in energy storage systems and electric vehicles. Their larger size makes them bad candidates for smaller devices like e-bikes and cellphones. Therefore, they are better suited for energy-intensive applications.

Pouch Cells

- Pouch cells are made to deliver more power than other cell types.
- They are also very efficient when it comes to space usage.
- Their soft plastic casing,
- They have the lowest mechanical resistance of all cell types.
- For this reason, an additional structure needs to be added during pouch cell assembly to protect them from mechanical damage.



Electric power Vs Energy in Batteries



Differences between Cylindrical cells and Prismatic cells

- **Size:** Prismatic cells are larger to cylindrical cells and contain more energy per cell.
- Connections: As Prismatic cells are larger fewer cells required to achieve the same amount of energy. And less manufacturing defects.
- Power: Cylindrical cells store less energy than prismatic cells but cylindrical cells store more power. Cylindrical cells discharge their energy faster than the prismatic cells so they are preferred for high performance applications.
- In EV industry, Cylindrical cells are more speeded now.

Cylindrical cells nomenclature

- Cylindrical cells need to be manufactured in a smaller format than other types of cells to make sure they dissipate heat well, helping prolong the battery life.
- That's why the most common cylindrical cell formats are the 18650 and 21700. Larger formats such as the 4680 are viable because their new internal design allows more efficient heat transfer to the thermal adhesives used in structural batteries.

An 18650 battery is a lithium-ion battery

- The name derives from the battery's specific measurements:
- 18mm x 65mm. For scale, that's larger than an AA battery. The 18650 battery has a voltage of 3.6v and has between 2600mAh and 3500mAh (mili-amp-hours).

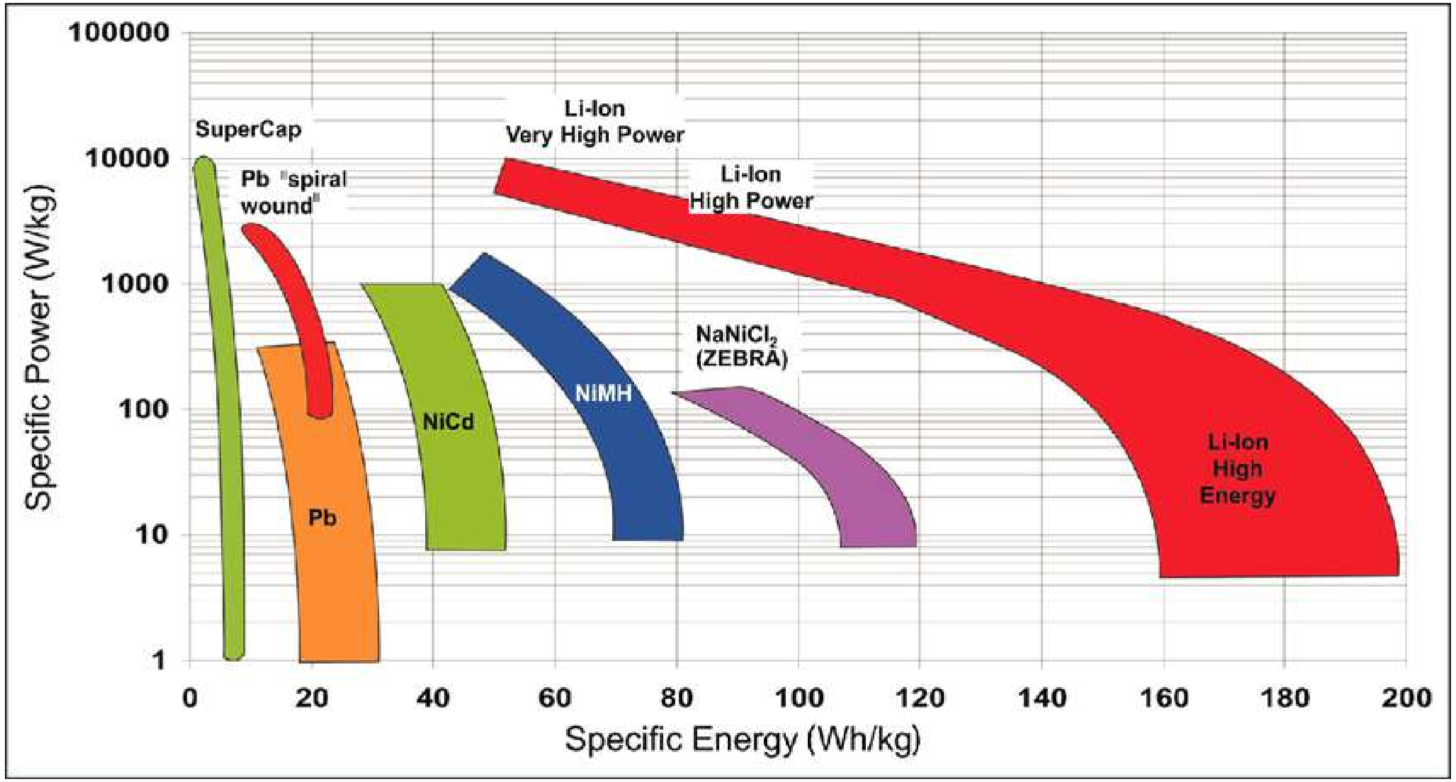
Other Cell types and their nomenclature

- 21700, 18650, 20700 and others simply refer to the physical size of the lithium-ion cell. For 18650, it's an 18 mm diameter x 65 mm length. 21700 is 21 mm x 70 mm.

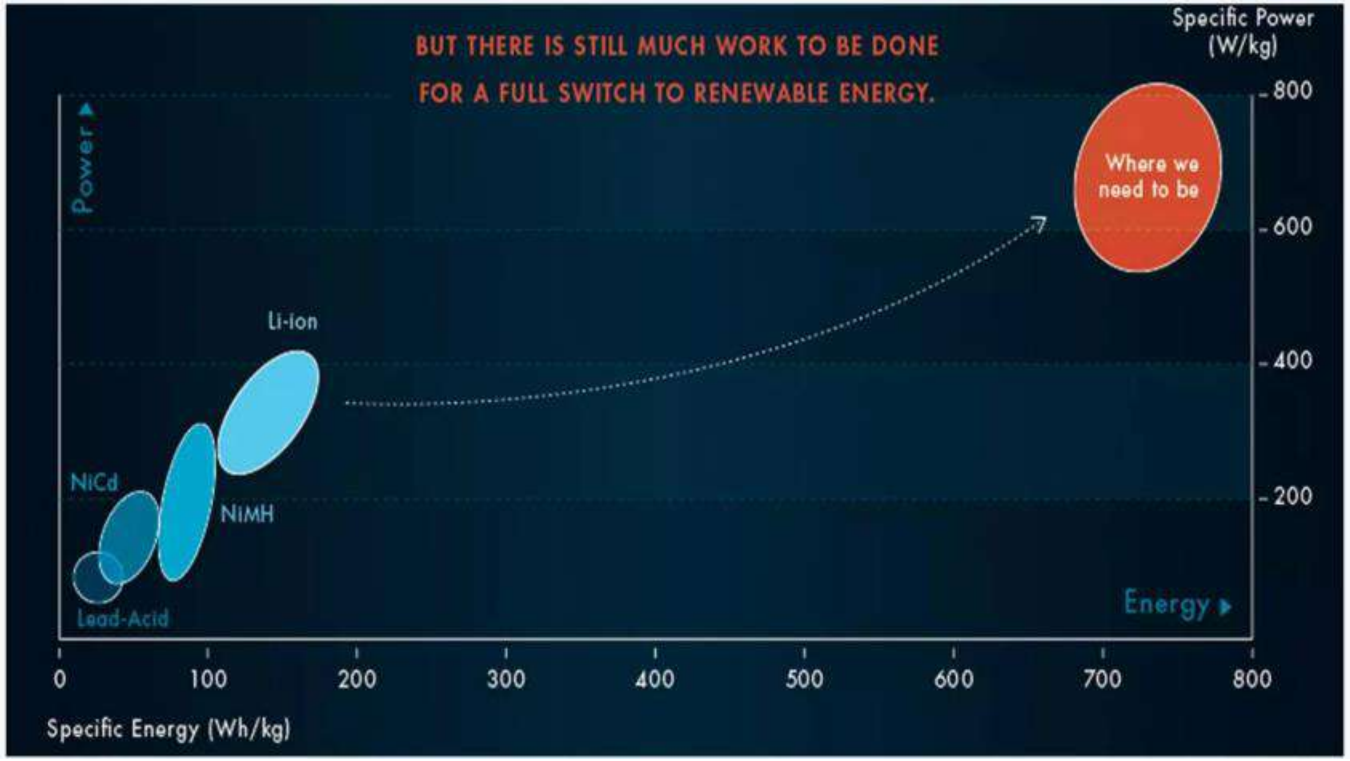
- 4680-type cylindrical lithium-ion battery (46 mm in diameter and 80 mm tall) cathode: NCM 811 (81.6% nickel) anode: graphite (no silicon), dry battery electrode technology.

Ragone plot EV batteries?

- A Ragone plot is **a logarithmic plot which is used to compare various energy- storage technologies including batteries**. The plot uses two indices for comparison, namely, the specific energy of the battery on the y-axis (typically in W·h/kg) and the specific power of the battery on the x-axis (typically in W/kg).



Future batteries need



Battery Parameters or Technical Specifications

Voltage(V): Normal voltage of the battery

Cut-Off voltage: Minimum allowable voltage that defines empty state of the battery.

Internal Resistance: Overall resistance within the battery. When the internal resistance increases, battery efficiency decreases due to more charging energy converted into heat.

State of Charge (SOC): Expression of present battery capacity to the percentage of maximum capacity.

Current rate (C- rate): measure of discharge current relative to its capacity. 1C rate indicates to the current at which the battery will fully discharge in one hour.

Capacity (Ah): The amount of electric charge stored in an hour.

Energy capacity (Wh): Total watt hours available when the battery is discharged from 100 percent State of charge to the cut – off voltage.

Depth of Discharge (DOD): Percentage of battery capacity that has been discharged expressed as a percentage of max. capacity. Discharge to atleast 80% DoD is referred to as a deep discharge.

Cycle life: No. of Discharge charge cycles of the battery.

Higher DOD, lower is the cycle life.

Lead acid batteries

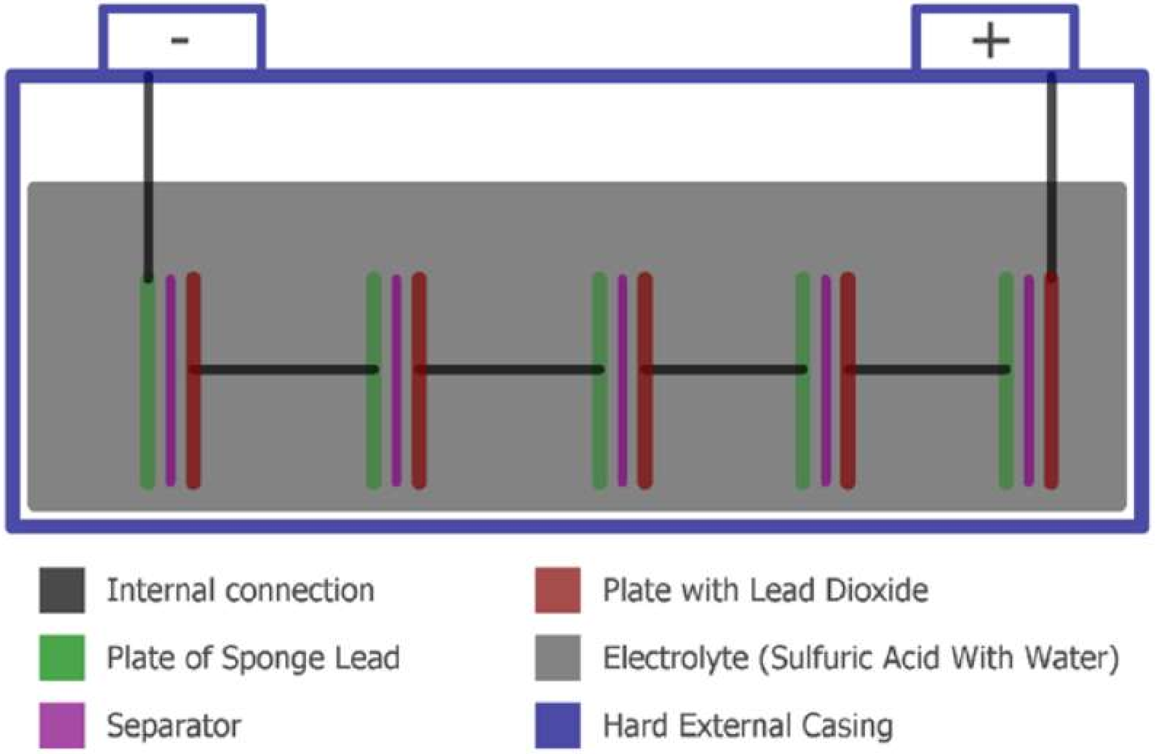
- The best known and most widely used battery for electric vehicles is the lead acid battery.
- The most common is the **SLI battery** used for motor vehicles for engine **S**tarting, vehicle **L**ighting and engine **I**gnition, however it has many other applications (such as communications devices, emergency lighting systems and power tools) due to its cheapness and good performance.
- It was first developed in **1860** by **Raymond Gaston Planté.**
- Strips of lead foil with coarse cloth in between were rolled into a spiral and immersed in a 10% solution of sulphuric acid.
- The cell was further developed by initially coating the lead with oxides, then by forming plates of lead oxide by coating an oxide paste onto grids. The electrodes were also changed to a tubular design.

Lead acid batteries

- Lead acid batteries are widely used in IC engine vehicles and as such are well known.
- However for electric vehicles, more robust lead acid batteries that withstand deep cycling and use a gel rather than a liquid electrolyte are used.
- These batteries are more expensive to produce.
- In the lead acid cells the negative plates have a spongy lead as their active material, whilst the **positive plates** have an **active material of lead dioxide.**
- The plates are immersed in an ***electrolyte of dilute sulphuric acid.***
- The sulphuric acid combines with the lead and the lead oxide to produce lead sulphate and water, electrical energy being released during the process.

Construction of Lead Acid Battery

- Lead is a chemical element (symbol is Pb and the atomic number is 82).
- It is a soft and malleable element.
- Acid can donate a proton or accept an electron pair when it is reacting.
- So, a battery, which consists of **Lead and anhydrous plumbic acid** (sometimes wrongly called as lead peroxide), is called as Lead Acid Battery.



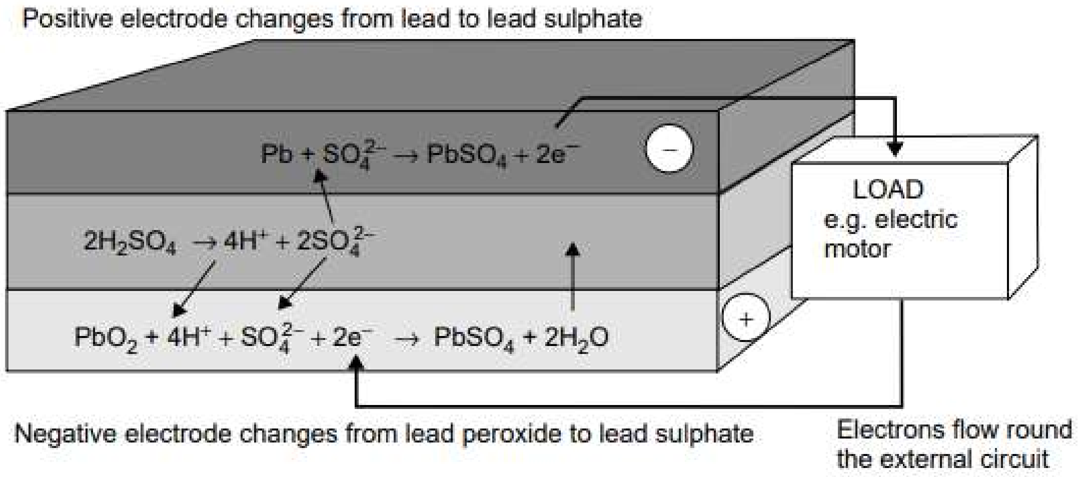
Working of Lead Acid Battery

- There are huge chemical process is involved in Lead Acid battery's charging and discharging condition.
- The diluted sulfuric acid H_2SO_4 molecules break into two parts when the acid dissolves.
- It will create positive ions 2H+ and negative ions SO_4-.
- Two electrodes are connected as plates, Anode and Cathode.
- Anode catches the negative ions and cathode attracts the positive ions.
- This bonding in Anode and SO_4- and Cathode with 2H+ interchange electrons and which is further react with the H2O or with the water (Diluted sulfuric acid, Sulfuric Acid + Water).
- The battery has two states of chemical reaction, **Charging and Discharging**.

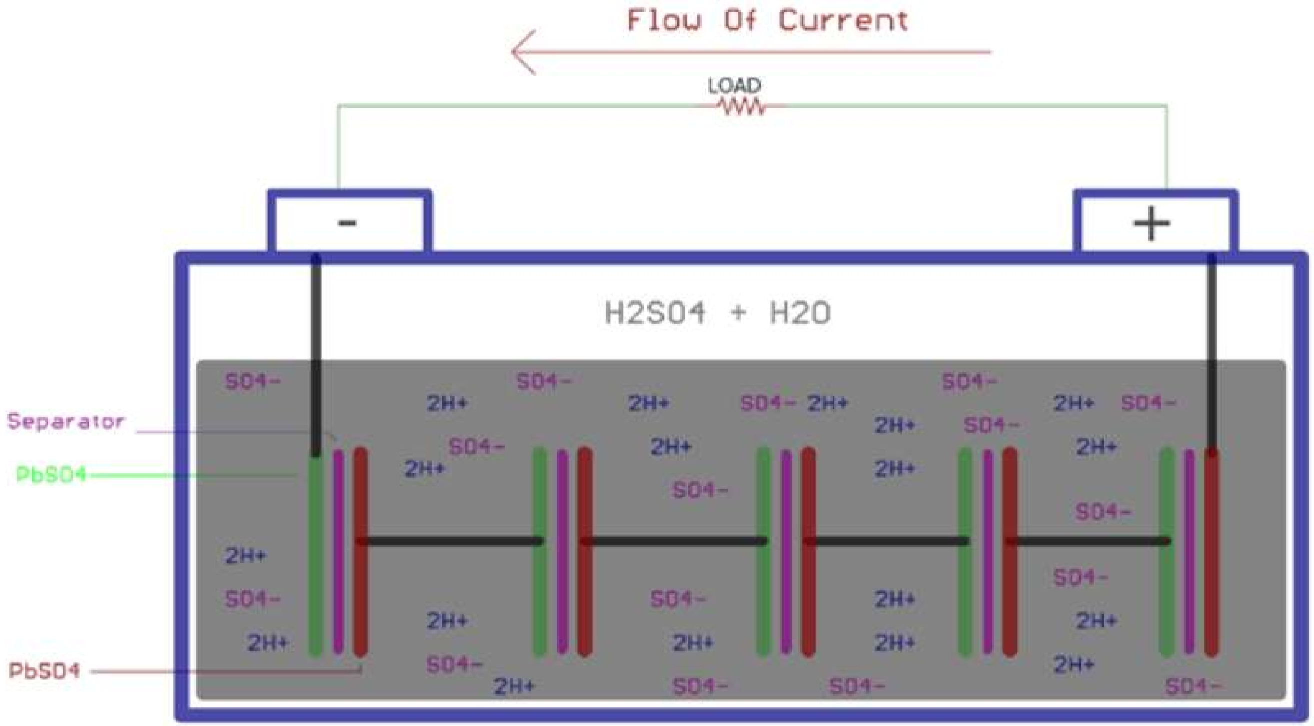
Lead Acid Battery Discharging

- The sulfuric acid is in the diluted form with typically 3:1 ratio with water and sulfuric acid.
- When the loads are connected across the plates, the sulfuric acid again breaks into positive ions 2H+ and negative ions SO_4.
- The hydrogen ions react with the PbO_2 and make PbO and water H_2O. PbO start reacting with the H_2SO_4 and creates $PbSO_4$ and H_2O.
- On the other side SO_4- ions exchange electrons from Pb, creating radical SO_4 which further creates $PbSO_4$ reacting with the Pb.

Lead Acid Battery Discharging



Reactions during the **discharge** of the lead acid battery.
Note that the electrolyte loses suphuric acid and gains water.

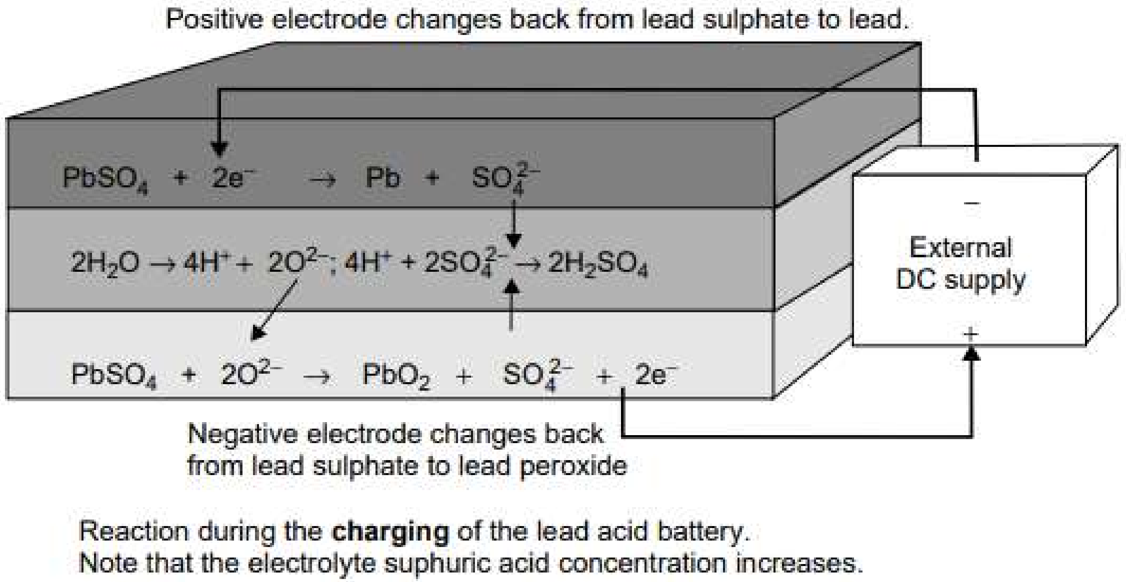


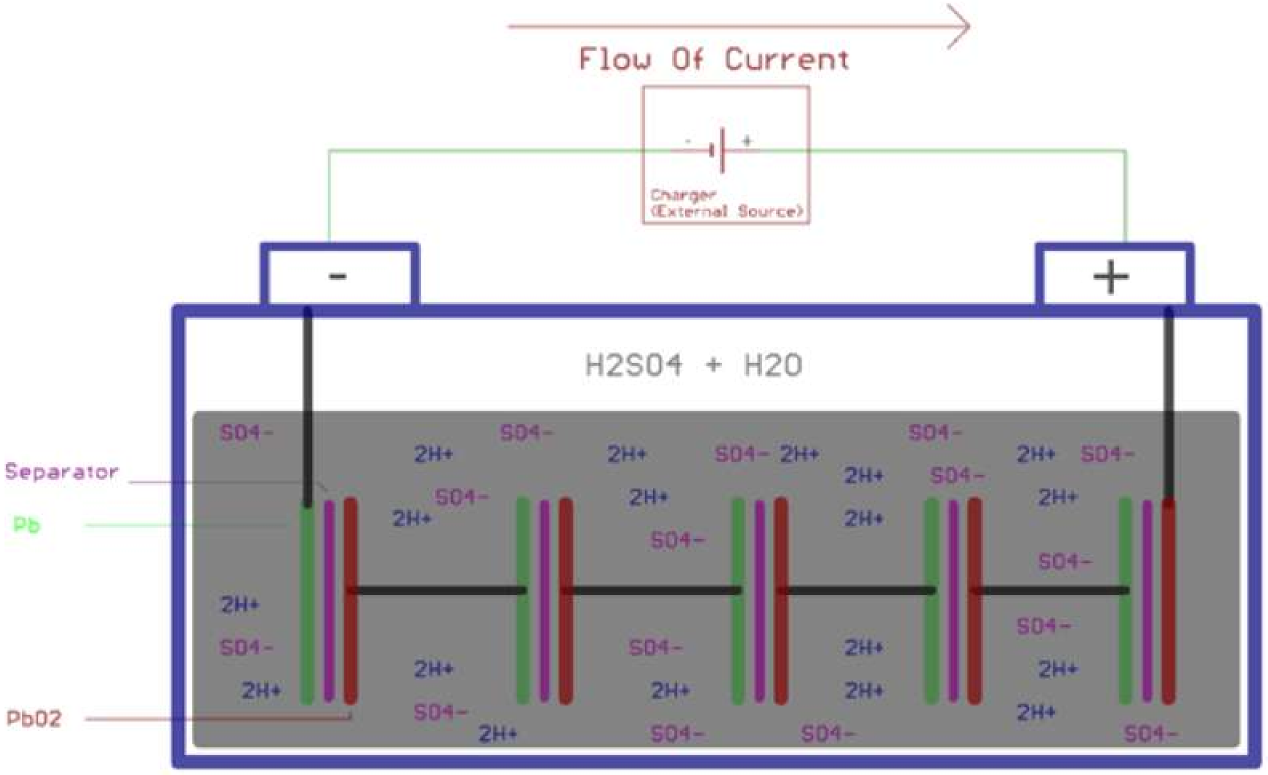
Lead Acid Battery Charging

- To charge a battery, we need to provide a voltage greater than the terminal voltage. So to charge a 12.6V battery, 13V can be applied.
- when the battery is connected with the charger, the sulfuric acid molecules break into two ions, positive ions 2H+ and negative ions SO_4-.
- The hydrogen exchange electrons with the cathode and become hydrogen, this hydrogen reacts with the $PbSO_4$ in cathode and form Sulfuric Acid (H_2SO_4) and Lead (Pb).
- On the other hand, SO_4- exchange electrons with anode and become radical SO_4.
- This SO_4 reacts with $PbSO_4$ of anode and create the lead peroxide PbO_2 and sulfuric acid (H_2SO_4).
- The energy gets stored by increasing the gravity of sulfuric acid and increasing the cell potential voltage.

Lead Acid Battery Charging

- Chemical reactions takes place at Anode and Cathode during the charging process.





Nominal battery parameters for lead acid batteries

Specific energy	20–35 $Wh.kg^{-1}$ depending on usage
Energy density	54–95 $Wh.L^{-1}$
Specific power	~250 $W.kg^{-1}$ before efficiency falls very greatly
Nominal cell voltage	2 V
Amphour efficiency	~80%, varies with rate of discharge & temp.
Internal resistance	Extremely low, ~0.022 Ω per cell for 1 Amphour cell
Commercially available	Readily available from several manufacturers
Operating temperature	Ambient, poor performance in extreme cold
Self-discharge	~2% per day, but see text below
Number of life cycles	Up to 800 to 80% capacity
Recharge time	8 h (but 90% recharge in 1 h possible)

- C-rate: A brand new battery with 10 Ah capacity theoretically can deliver 1 A current for 10 hours at room temperature. Of course, in practice this is seldom the case due to several factors. Therefore, the C-rate is used, which is a measure of the rate of discharge of the battery relative to its capacity. It is defined as the multiple of the current over the discharge current that the battery can sustain over one hour. For example, a C-rate of 1 for a 10 Ah battery corresponds to a discharge current of 10 A over 1 hour. A C-rate of 2 for the same battery would correspond to a discharge current of 20 A over half an hour. Similarly, a C-rate of 0.5 implies a discharge current of 5 A over 2 hours. In general, it can be said that a C-rate of n corresponds to the battery getting fully discharged in 1/n hours, irrespective of the battery capacity

Few websites tells about EV terminology

- https://www.myev.com/research/ev-101/ev-terminology
- https://evsafecharge.com/ev-terms-glossary/
- https://batteryuniversity.com/articles
- https://www.carandbike.com/news/types-of-batteries-used-in-electric-vehicles-their-parameters-2754393

Energy storage

- **Lithium-Ion Batteries**
- **Nickel-Metal Hydride Batteries**
- **Lead-Acid Batteries**
- **Ultra capacitors**

Image of Electric vehicle batteries

- https://afdc.energy.gov/vehicles/electric_batteries.html

Lead-Acid Batteries

- High power
- Inexpensive
- Safe
- Reliable

Disadvantages:

- Low specific energy
- Poor cold-temperature performance
- Short calendar and lifecycle

- Advanced high-power lead-acid batteries are being developed, but these batteries are only used in commercially available electric-drive vehicles for ancillary loads

Nickel-Metal Hydride Batteries

- Used in Computers Medical equipment's. Also in HEVs.
- Good Specific energy and specific power capabilities.
- Much longer life cycle than lead-acid batteries
- Safe and abuse tolerant.

Challenges

- High cost
- High self-discharge
- Heat generation at high temperatures,
- Need to control hydrogen loss

Lithium-Ion Batteries

Advantages:

- Portable: As they are portable electronic equipment like cell phones, laptops are widely using these batteries.
- High energy per mass unit.
- High power-to-weight ratio
- High energy efficiency
- Good high-temperature performance
- Low self-discharge.
- Most components of lithium-ion batteries can be recycled

Disadvantages:

- Cost is high: As most of the All-Electric vehicles using Li-ion batteries, R&D is ongoing to reduce their relatively high cost, extend the life and also addressing the safety concerns regard to over heating.
- The U.S. Department of Energy is also supporting the Lithium-Ion Battery Recycling Prize to develop and demonstrate profitable solutions for collecting, sorting, storing, and transporting spent and discarded lithium-ion batteries for eventual recycling and materials recovery.

III Year B.Tech. EEE II-Semester

Electric & Hybrid Vehicles
Course Code: PE116CW 3
(Professional Elective-II)

Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

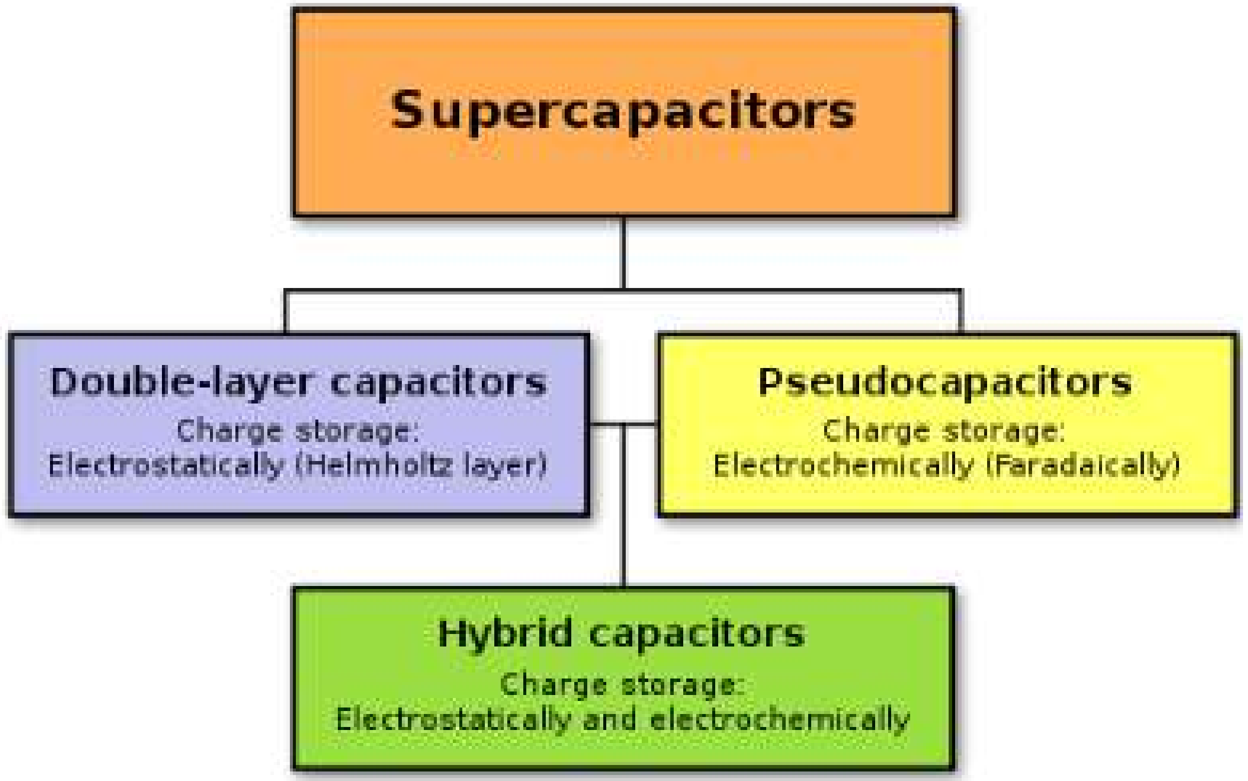
UNIT 2: (~8 Lecture Hours)

- Energy storage:
- Introduction to energy storage requirements in hybrid and electric vehicles.
- Electro chemical batteries and its analysis,
- **Ultra capacitors and its analysis,**
- Ultra high speed flywheels and its analysis,
- Hybridization of Energy storages.

Ultracapacitors

- Because of the frequent stop/go operation of EVs and HEVs, the discharging and charging profile of the energy storage is highly varied.
- The average power required from the energy storage is much lower than the peak power of relatively short duration required for acceleration and hill climbing.
- The ratio of the peak power to the average power can be over 10:1.
- In fact, the energy involved in the acceleration and deceleration transients is roughly two thirds of the total amount of energy over the entire vehicle mission in urban driving.
- In HEV design, the peak power capacity of the energy storage is more important than its energy capacity, and usually constrains its size reduction.

Ultra Capacitors



Ultracapacitor also called as super capacitor
It is a high capacity capacitor

Features of Ultracapacitor

- Ultracapacitors, also known as supercapacitors or electric double-layer capacitors (EDLCs), are energy storage devices
- **High Power Density: T**hey can deliver high amounts of power quickly. This makes them ideal for applications that require bursts of energy, such as electric vehicles or regenerative braking systems.
- **Rapid Charging and Discharging:** Ultracapacitors can be charged and discharged very quickly, often in a matter of seconds. This makes them useful for applications where rapid energy storage and release is required.
- **Long Cycle Life:** Ultracapacitors have a longer cycle life than most batteries, meaning that they can be charged and discharged more times before their performance starts to degrade. This makes them more durable and cost-effective in the long run.
- **Wide Operating Temperature Range:** Operating Temperatures are between -40°C to +85°C, making them suitable for use in extreme environments.
- **Low Maintenance:** Ultracapacitors require little to no maintenance, as they do not have the same chemical reactions that batteries do. This reduces the overall cost of ownership.
- **Environmentally Friendly: D**o not contain hazardous chemicals or heavy metals, making them more environmentally friendly than traditional batteries.

Construction of Ultracapacitor

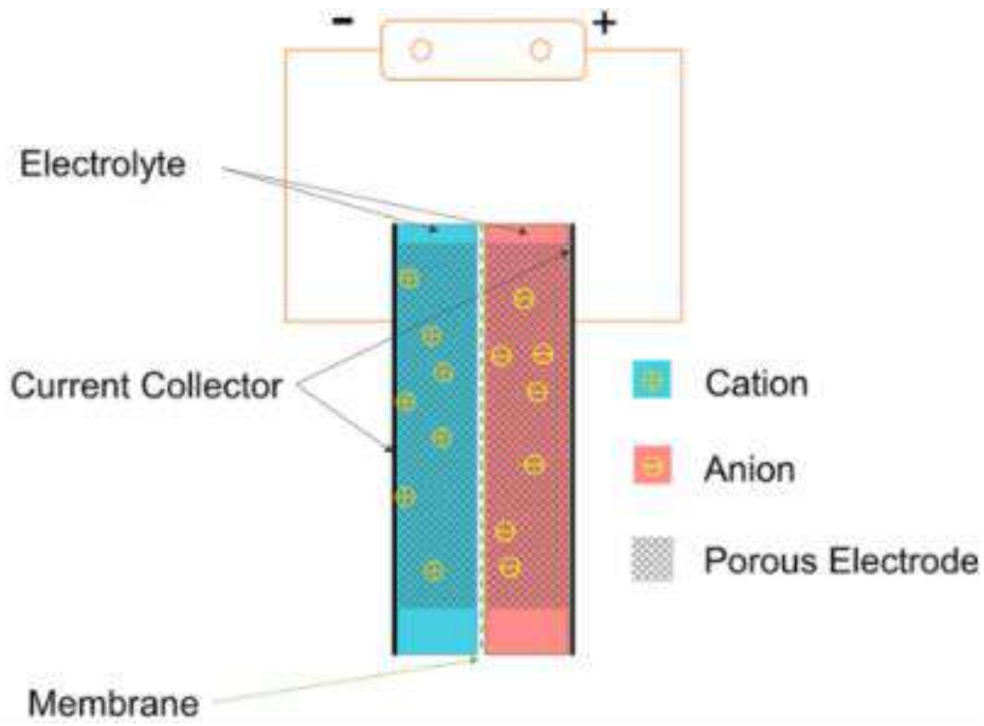
- Consists of two electrodes, a separator, and an electrolyte.

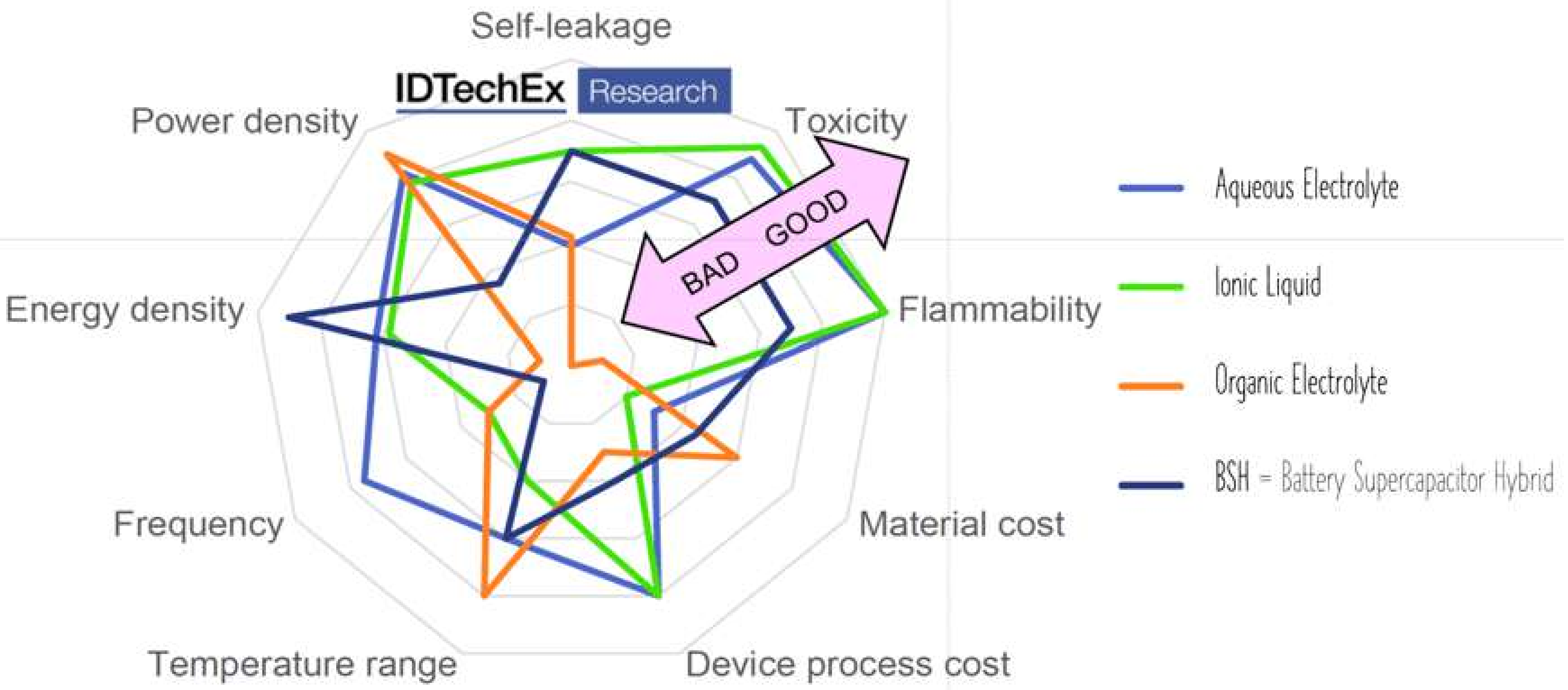
- **Electrodes:** made of activated carbon or another conductive material with a high surface area, which provides a large area for charge storage.
- **The separator** is a thin layer of insulating material that prevents the electrodes from touching each other, while allowing ions to pass through.
- **The electrolyte** is a liquid or gel substance that contains ions, which are used to store and transport charge.

Construction of Ultracapacitor

- steps involved in construction:
- Electrode preparation: The electrodes are typically made by applying a conductive material, such as activated carbon, to a substrate. This substrate may be a thin metal foil or a conductive polymer.
- Electrode assembly: The electrodes are then assembled together with the separator, typically in a stacked or rolled configuration. The separator is placed between the electrodes to prevent them from touching.
- Electrolyte filling: The electrolyte is then added to the ultracapacitor, typically through a small hole or port in the casing. The electrolyte wets the surface of the electrodes and fills the space between them, allowing ions to move freely.
- Sealing: The ultracapacitor is then sealed to prevent leakage of the electrolyte solution.
- Electrical Connections: Electrical connections are made to the two electrodes to allow the flow of current in and out of the ultracapacitor.
- Once the ultracapacitor is constructed, it can store energy by accumulating charge on the surface of the electrodes. When a load is connected to the ultracapacitor, the stored energy is released, providing a high burst of power.

Ultra Capacitor Construction




Self-leakage
IDTechEx Research
Power density
Toxicity
Energy density
Flammability
Frequency
Material cost
Temperature range
Device process cost
BAD
GOOD
Aqueous Electrolyte
Ionic Liquid
Organic Electrolyte
BSH = Battery Supercapacitor Hybrid

Working

- The energy stored in an ultracapacitor is proportional to the amount of charge that can be accumulated on the surface of the electrodes. The amount of charge that can be stored is determined by the surface area of the electrodes and the distance between them, as well as the properties of the electrolyte solution.
- When a load is connected to the ultracapacitor, the stored energy is released. This can happen very quickly, as the charge stored on the surface of the electrodes can be released almost instantaneously. The amount of energy that can be released is proportional to the amount of charge stored on the electrodes.
- Ultracapacitors can be charged and discharged very quickly, often in a matter of seconds, due to the low resistance of the electrodes and the high conductivity of the electrolyte solution. They also have a longer cycle life than most batteries, as there are no chemical reactions involved in the charge and discharge process, and the electrodes do not degrade over time.

Ultracapacitors

- Based on present battery technology, battery design has to carry out the trade-off among the specific energy and specific power and cycle life.
- The difficulty in simultaneously obtaining high values of specific energy, specific power, and cycle life has led to some suggestions that the energy storage system of EV and HEV should be a hybridization of an energy source and a power source.
- The energy source, mainly batteries and fuel cells, has high specific energy whereas the power source has high specific power.
- The power sources can be recharged from the energy source during less demanding driving or regenerative braking. The power source that has received wide attention is the ultracapacitor.

Features of Ultracapacitors

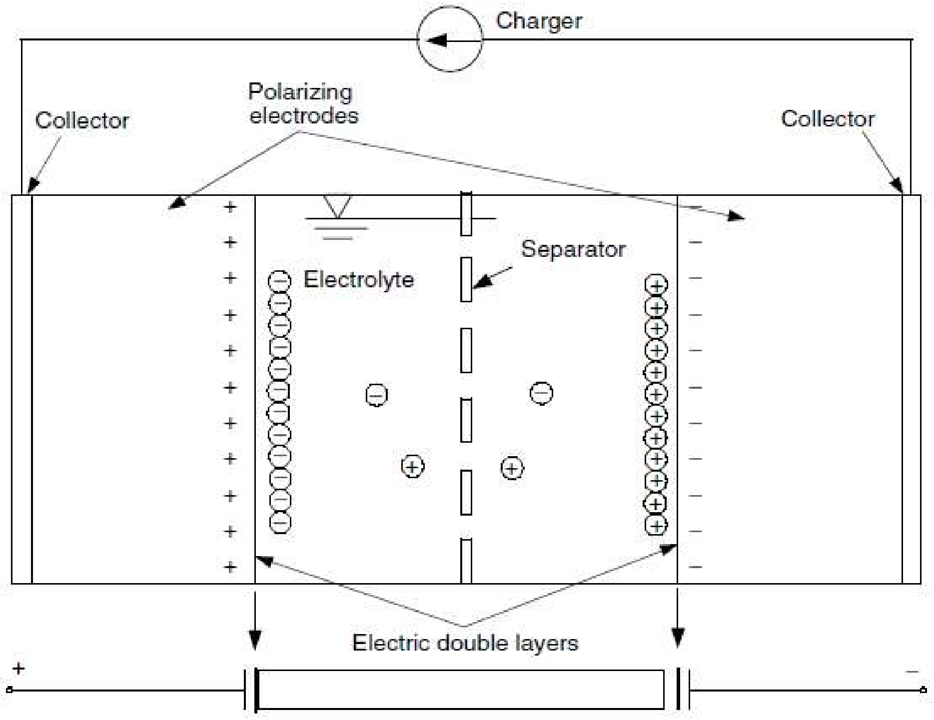
- The ultracapacitor is characterized by much higher specific power, but much lower specific energy compared to the chemical batteries.
- Its specific energy is in the range of a few watt-hours per kilogram.
- However, its specific power can reach up to 3 kW/kg, much higher than any type of battery.
- Due to their low specific energy density and the dependence of voltage on the SOC, it is difficult to use ultracapacitors alone as an energy storage for EVs and HEVs.
- Nevertheless, there are a number of advantages that can result from using the ultracapacitor as an auxiliary power source.

Features of Ultracapacitors

- One promising application is the so-called battery and ultracapacitor hybrid energy storage system for EVs and HEVs.
- Specific energy and specific power requirements can be decoupled, thus affording an opportunity to design a battery that is optimized for the specific energy and cycle life with little attention being paid to the specific power.
- Due to the load leveling effect of the ultracapacitor, the high-current discharging from the battery and the high-current charging to the battery by regenerative braking is minimized so that the available energy, endurance, and life of the battery can be significantly increased.

Basic Principles of Ultracapacitors

- Double-layer capacitor technology is the major approach to achieve the ultracapacitor concept. And the basic principle is as shown in fig.
- Two carbon rods are immersed in a thin sulfuric acid solution. Each rod is separated with each other and charged with voltage increasing from 0 to 1.5V.
- No change occurs up to 1V. At 1.2V, a small bubble appears in the surface of the electrodes. Those bubbles indicate electrical decomposition of water.
- Current does not flow below the decomposition voltage. And an electric double layer then occurs at the boundary of electrode and electrolyte. The electrons are charged across the double layer and for the capacitor.
- An electrical double layer works as an insulator only below the decomposing voltage.



Basic Principles of Ultracapacitors

- The stored energy $E_{cap} = \frac{1}{2} CV^2$
  - Where C is Capacitance in Farads
  - V is the usable voltage in volts.
- As per the equation, higher the voltage, larger the energy density capacitors.
- So, capacitors rated voltage with an aqueous electrolyte is 0.9V per cell. With nonaqueous electrolyte it is 2.3 to 3.3 V per each cell.
- Usage of electric double layer in place of plastic or aluminum films in a capacitor is more advantageous. As the double layer is very thin (as thin as one molecule with no pin holes) and the capacity per area is quite large at 2.5 to 5 μF/ cm^2.

Basic Principles of Ultracapacitors

- Even if a few μF/ cm^2 are obtainable, the energy density of capacitors is not large when using aluminum foil.
- For increasing capacitance, electrodes are made from specific materials that have a very large area, such as activated carbons, which are famous for their surface areas of 1,000 to 3,000 m^2 /g.
- To those surfaces, ions are adsorbed and result in 50 F/g

  (1,000 m^2 /g x 5 F/c m^2 x 10,000 c m^2 / m^2 = 50 F/g).
- Assuming that the same weight of electrolyte is added, 25 F/g is quite a large capacity density.
- Nevertheless, the energy density of these capacitors is far smaller than secondary batteries; the typical specific energy of ultracapacitors at present is about 2 Wh/kg, ie., only 1/20 of 40 Wh/kg, which is the available value of typical lead-acid batteries.

Performance of Ultracapacitors

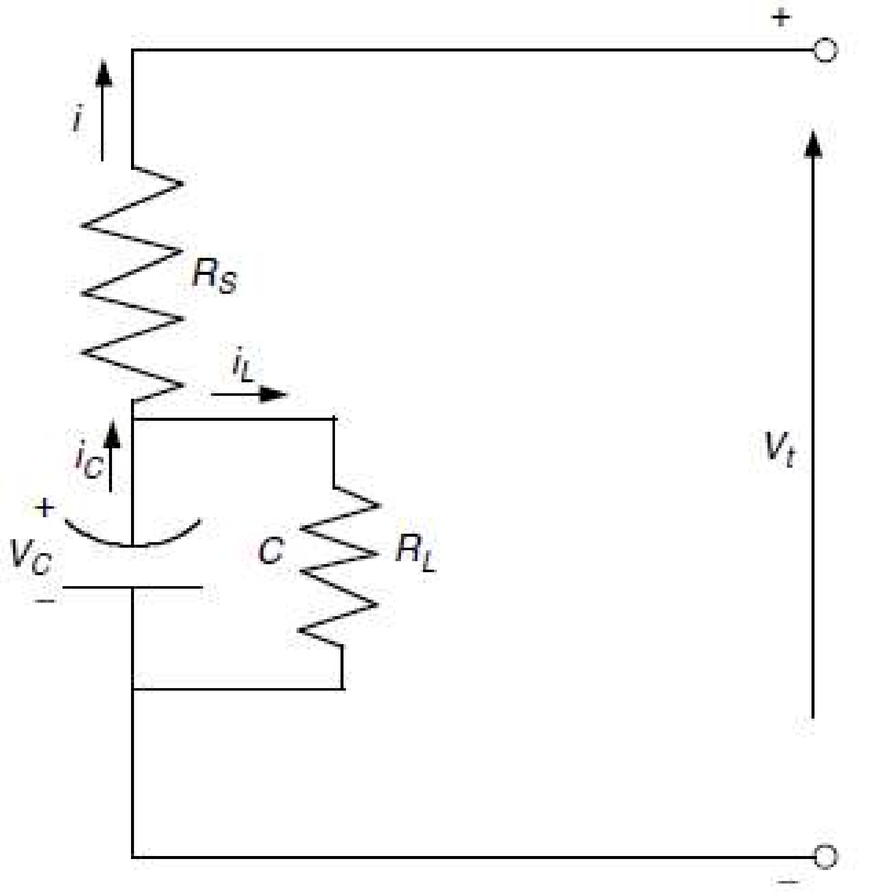
- The performance of an ultracapacitor may be represented by terminal voltages during discharge and charge with different current rates.
- There are three parameters in a capacitor:
  - The capacitance itself (its electric potential V_c),
  - The series resistance R_s, and
  - The dielectric leakage resistance, R_L.
- The terminal voltage of the ultracapacitor during discharge can be expressed as

$$V_t = V_c - i\, R_s \rightarrow 1$$

Electric potential of a capacitor can be expressed by

$$\frac{dV_c}{dt} = -\left(\frac{i+i_L}{C}\right) \rightarrow 2$$

i_L is the leakage current where $i_L = \frac{V_c}{R_L} \rightarrow 3$



C is the capacitance of the ultracapacitor

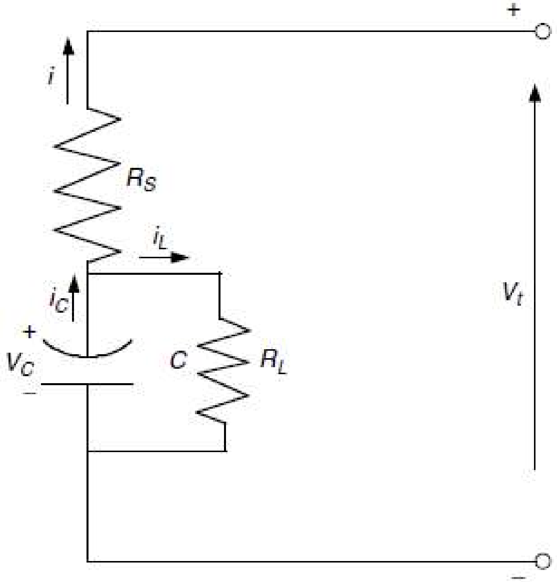
Performance of Ultracapacitors

Substituting equation 3in equation 2,

$$\frac{dV_c}{dt} = \frac{V_c}{CR_L} - \left(\frac{i}{C}\right).$$

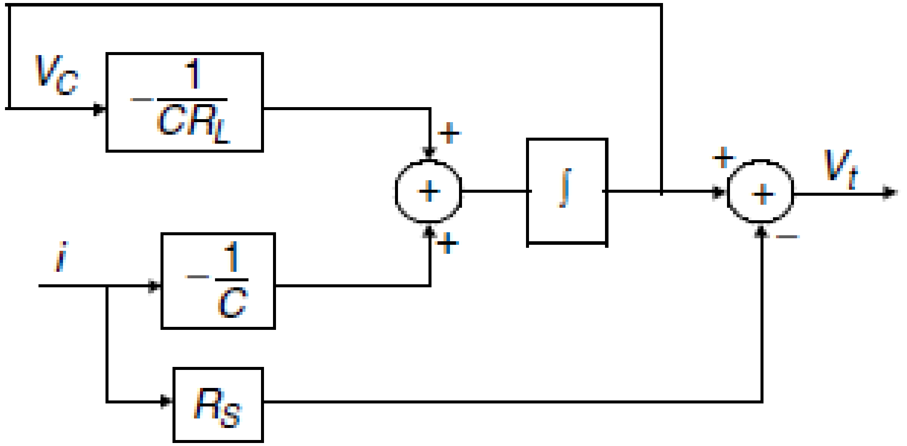
Therefore $V_c = \left[V_{co}\int_0^t \frac{i}{C}\, e^{t/CR_L} dt\right] e^{t/CR_L}$

where i is the discharge current, which is a function of time in real operation.



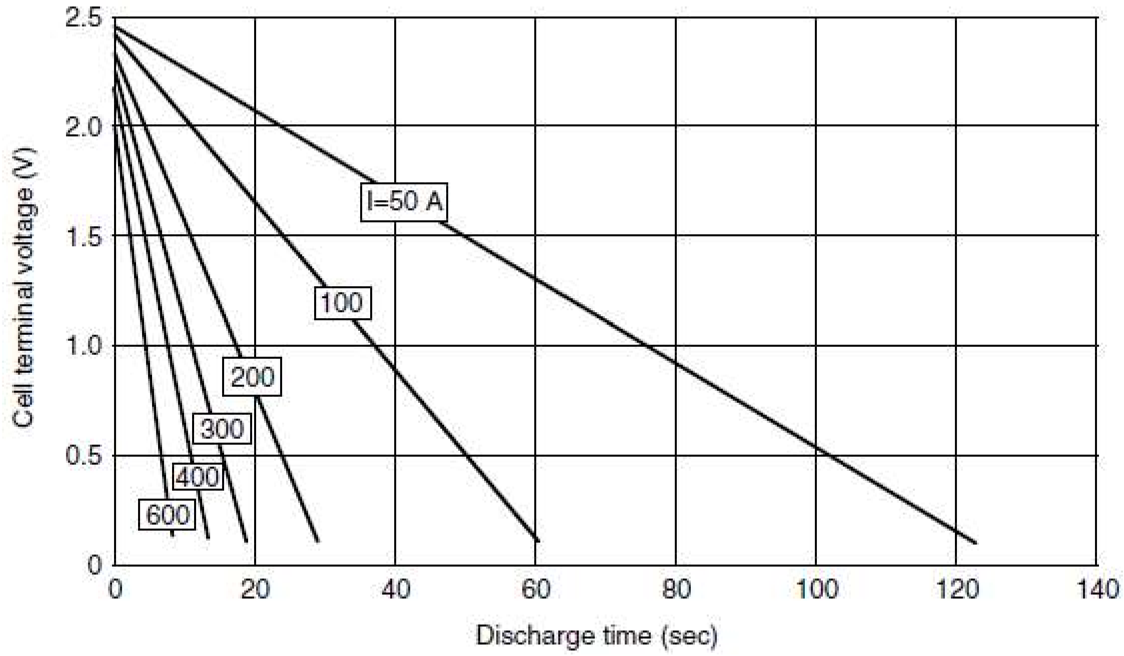
Block Diagram of the Ultracapacitor model

$$V_c = \left[V_{co}\int_0^t \frac{i}{C}\, e^{t/CR_L} dt\right] e^{t/CR_L}$$



Performance of Ultracapacitors

- At different discharge current rates, voltage decreases linearly with discharge time.
- At a large discharge current rate, the voltage decreases much faster than at a small current rate.



Performance of Ultracapacitors

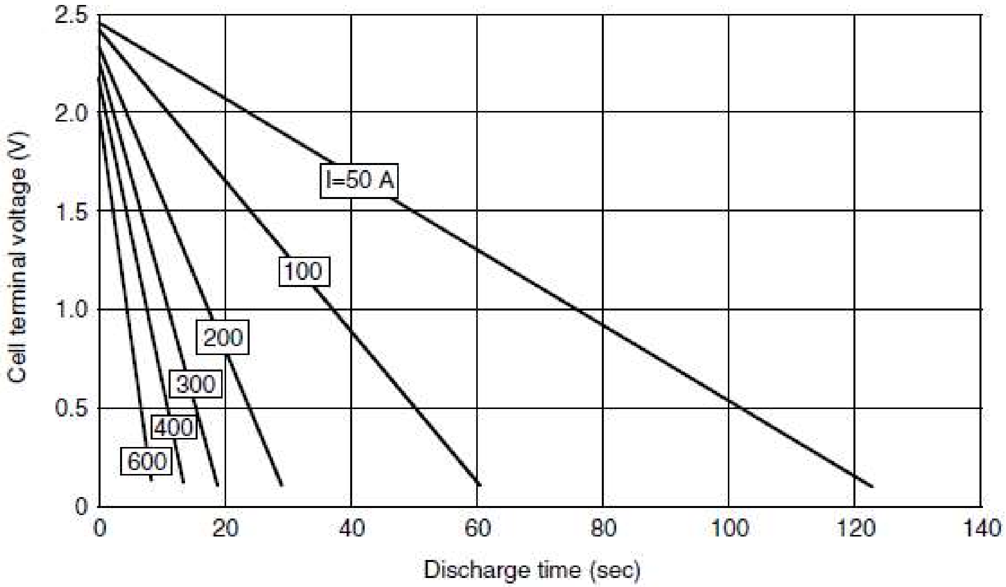
- Operation efficiency in discharging and charging can expressed as

Discharging:

$$\eta_d = \frac{V_t I_t}{V_C I_C} = \frac{(V_C - I_t R_s) I_t}{V_C (I_t + I_L)}$$

And

Charging: $$\eta_c = \frac{V_c I_c}{V_t I_t} = \frac{V_C (I_t - I_L)}{(V_C + I_t R_s) I_t}$$



In actual operation, I_L is very small and can be ignored. Thus,

$$\eta_d = \frac{V_t I_t}{V_C I_C} = \frac{(V_C - I_t R_s)}{V_C} = \frac{V_t}{V_C}$$

And Charging: $$\eta_c = \frac{V_C}{V_C + R_s I_t} = \frac{V_c I_c}{V_t I_t}$$

Ultracapacitor Technologies

- According to the goals set by the U.S. Department of Energy for the inclusion of ultracapacitors in EVs and HEVs, the near-term specific energy and specific power should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kg and 1600 W/kg.
- So far, none of the available ultracapacitors can fully satisfy these goals.
- Nevertheless, some companies are actively engaged in the research and development of ultracapacitors for EV and EHV applications.
- Maxwell Technologies has claimed that its power BOOSTCAP ultracapacitor cells (2600 F at 2.5 V) and integrated modules (145 F at 42 V and 435 F at 14 V) are in production.
- The technical specifications are listed in Table 10.3.

Ultracapacitor Technologies

Technical Specifications of the Maxwell Technologies Ultracapacitor Cell and Integrated Modules[5]

	BCAP0010 (Cell)	BMOD0115 (Module)	BMOD0117 (Module)
Capacitance (farads, −20%/+20%)	2600	145	435
maximum series resistance ESR at 25°C (mΩ)	0.7	10	4
Voltage (V), continuous (peak)	2.5 (2.8)	42 (50)	14 (17)
Specific power at rated voltage (W/kg)	4300	2900	1900
Specific energy at rated voltage (Wh/kg)	4.3	2.22	1.82
Maximum current (A)	600	600	600
Dimensions (mm) (reference only)	60 × 172 (Cylinder)	195 × 165 × 415 (Box)	195 × 265 × 145 (Box)
Weight (kg)	0.525	16	6.5
Volume (l)	0.42	22	7.5
Operating temperature[a] (°C)	−35 to +65	−35 to +65	−35 to +65
Storage temperature (°C)	−35 to +65	−35 to +65	−35 to +65
Leakage current (mA) 12 h, 25°C	5	10	10

Ultrahigh-Speed Flywheels

- The use of flywheels for storing energy in mechanical form is not a new concept.
- More than 25 years ago, the Oerlikon Engineering Company in Switzerland made the first passenger bus solely powered by a massive flywheel.
- This flywheel, which weighed 1500 kg and operated at 3000 rpm, was recharged by electricity at each bus stop.
- The traditional flywheel is a massive steel rotor with hundreds of kilograms that spins on the order of ten hundreds of rpm.
- On the contrary, the advanced flywheel is a lightweight composite rotor with tens of kilograms and rotates on the order of 10,000 rpm; it is the so-called ultrahigh-speed flywheel.
- The concept of ultrahigh-speed flywheels appears to be a feasible means for fulfilling the stringent energy storage requirements for EV and HEV applications, namely high specific energy, high specific power, long cycle life, high-energy efficiency, quick recharge, maintenance free characteristics, cost effectiveness, and environmental friendliness.

Operation Principles of Flywheels

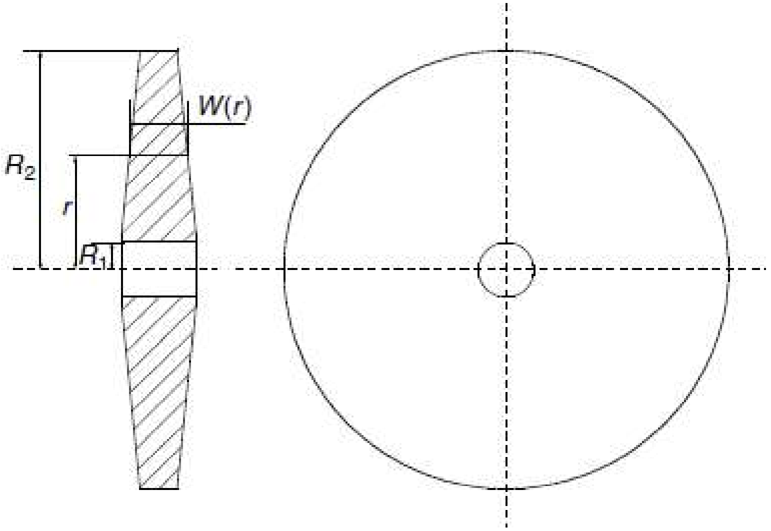
- A rotating flywheel stores energy in the kinetic form as $E_f = \frac{1}{2} J_f \omega_f^2$

J_f → Moment of inertia of the flywheel in kgm^2/sec

and ω_f is the angular velocity of the flywheel in rad/sec.

It indicates that the energy stored in a flywheel is proportional to the moment of inertia of the flywheel and flywheel rotating speed squared.

- A lightweight flywheel should be designed to achieve moment of inertia per unit mass and per unit volume by properly designing its geometric shape.



Geometry of a typical flywheel

III Year B.Tech. EEE II-Semester

Electric & Hybrid Vehicles

Course Code: PE116CW 3

(Professional Elective-II)

Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

UNIT 3: (~8 Lecture Hours)

Electric Vehicles:

- Configurations of Electric vehicles
- Performance of Electric vehicles
  - Traction motor characteristics,
  - Tractive effort and transmission requirement:
    - Gears
    - Clutch
    - Brakes
    - Ideal gearbox
    - EV motor sizing
  - Tractive effort in normal driving
  - Energy consumption

Electric Vehicles

- Electric vehicles (EVs) use an electric motor for traction, and chemical batteries, fuel cells, ultracapacitors, and/or flywheels for their corresponding energy sources.
- The electric vehicle has many advantages over the conventional internal combustion engine vehicle (ICEV), such as an absence of emissions, high efficiency, independence from petroleum, and quiet and smooth operation.
- The operational and fundamental principles in EVs and ICEVs are similar, however, some differences between ICEVs and EVs, such as the use of gasoline tanks vs. batteries, ICE vs. electric motor, and different transmission requirements.
- This unit focuses on
  - power train design
  - key components including traction motor and
  - energy storages.

Configurations of Electric Vehicles

Initially, the EV was mainly converted from the existing ICEV by replacing the internal combustion engine and fuel tank with an electric motor drive and battery pack while retaining all the other components, as shown in Figure 1.

Drawbacks are

- heavy weight
- lower flexibility and
- performance degradation

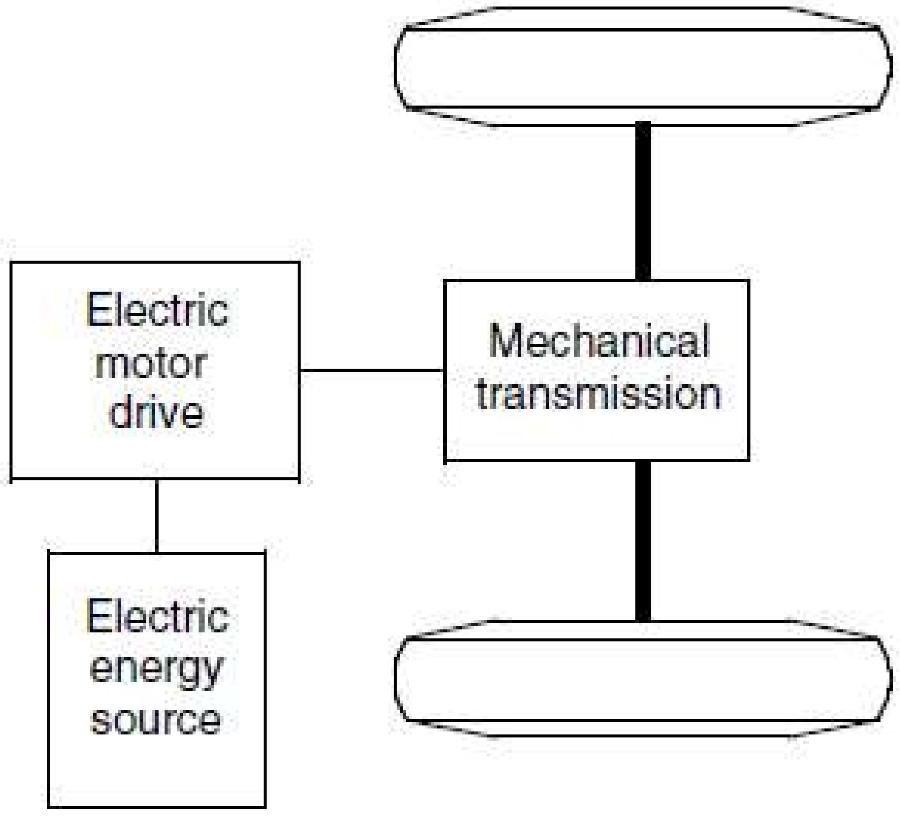
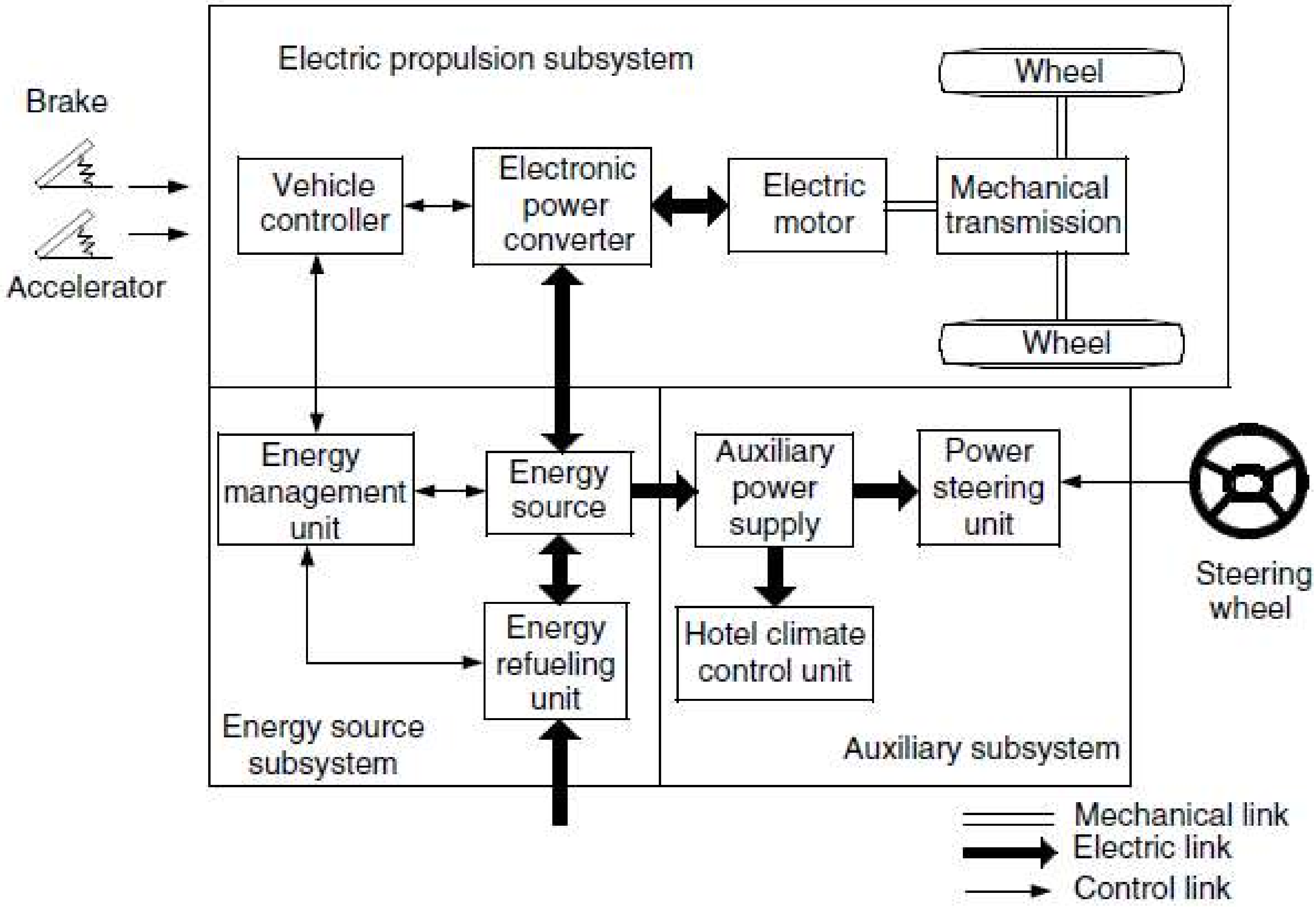


Fig1: Primary electric vehicle power train

Conceptual illustration of general EV configuration

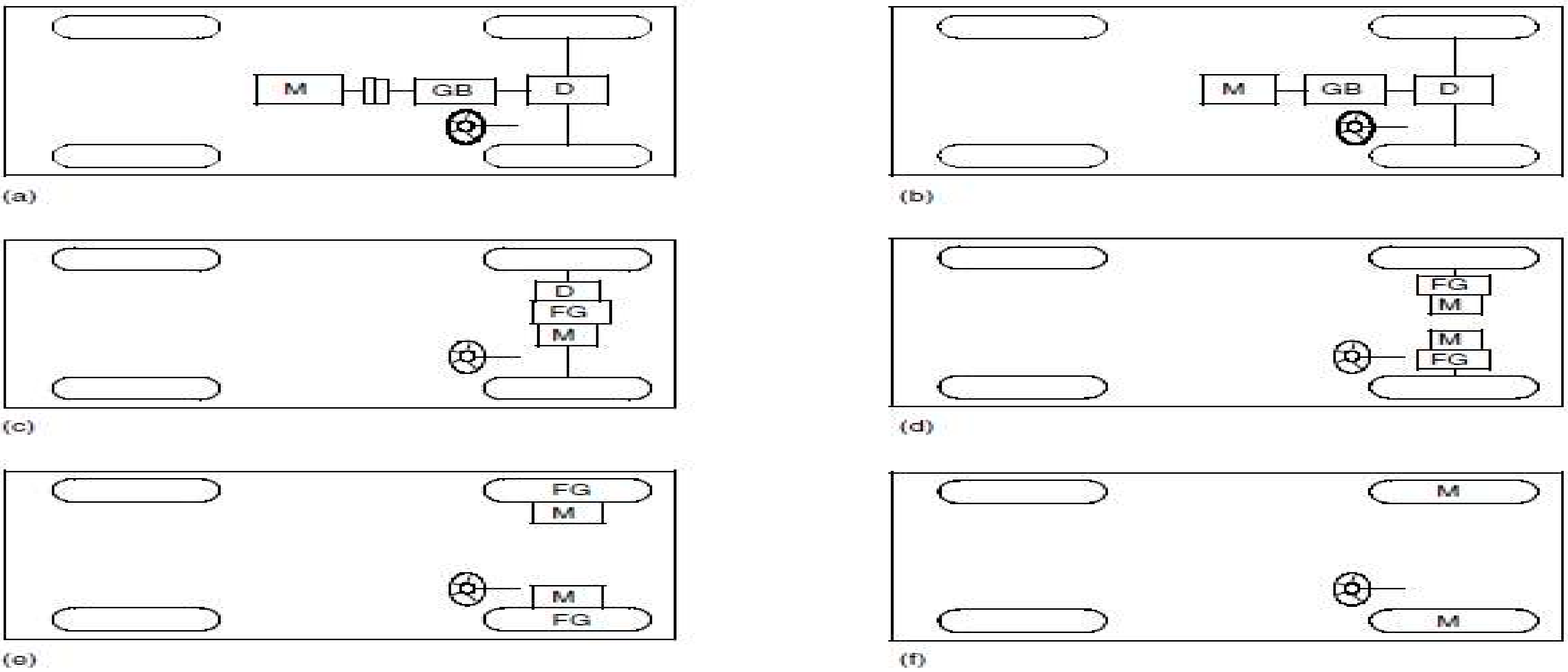


The drive train consists of three major subsystems:

- Electric motor propulsion
- Energy source and
- Auxiliary.

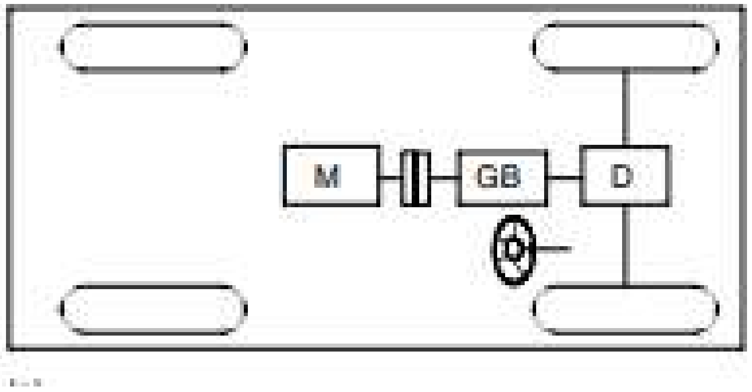
The electric propulsion subsystem	The energy source subsystem	The auxiliary subsystem
A vehicle controller Power electronic converter Electric motor Mechanical transmission, and Driving wheels	• The energy source, • The energy management unit, and • The energy refueling unit.	• The power steering unit, • The hotel climate control unit, and • The auxiliary supply unit.

Possible EV configurations



C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
M: Electric motor

EV configurations (a)



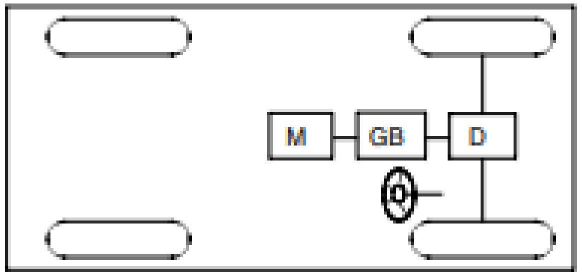
C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
M: Electric motor

An electric propulsion replaces the IC engine of a conventional vehicle drive train.

It consists of electric motor, clutch, Gearbox, and Differential.

- The clutch and gearbox may be replaced by automatic transmission.
- The clutch is used to connect or disconnect the power of the electric motor from the driven wheels.
- The gearbox provides a set of gear ratios to modify the speed-power (torque) profile to match the load requirement.
- The differential is a mechanical device (usually a set of planetary gears), which enables the wheels of both sides to be driven at different speeds when the vehicle runs along a curved path.

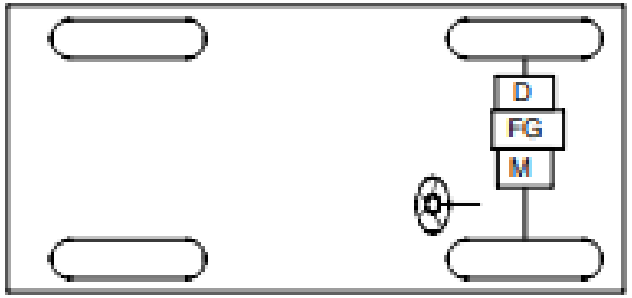
EV configurations (b)



- With an electric motor that has constant power in a long speed range, a fixed gearing can replace the multispeed gear box and reduce the need for a clutch.
- This configuration not only reduces the size and weight of the mechanical transmission, but also simplifies the drive train control because gear shifting is not needed.

C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
M: Electric motor

EV configurations (c)

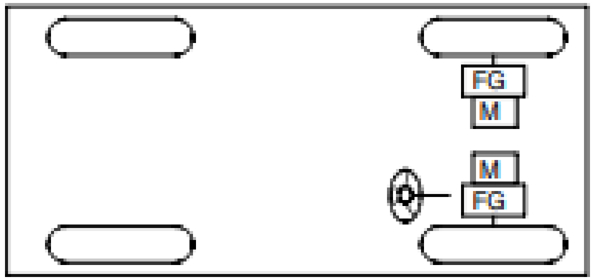


C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
M: Electric motor

Similar to the drive train in (b),

- the electric motor, the fixed gearing, and the differential can be further integrated into a single assembly while both axles point at both driving wheels.
- The whole drive train is further simplified and compacted.

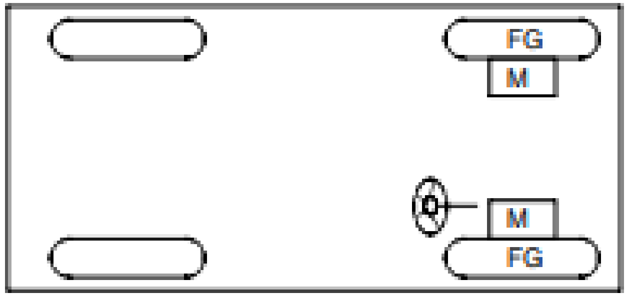
EV configurations (d)



- The mechanical differential is replaced by using two traction motors.
- Each of them drives one side wheel and operates at a different speed when the vehicle is running along a curved path.

C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
M: Electric motor

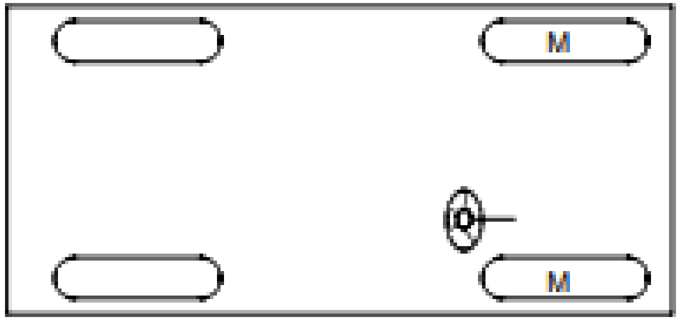
EV configurations (e)



C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
M: Electric motor

- In order to further simplify the drive train, the traction motor can be placed inside a wheel.
- This arrangement is the so-called in wheel drive. A thin planetary gear set may be used to reduce the motor speed and enhance the motor torque.
- The thin planetary gear set offers the advantage of a high-speed reduction ratio as well as an inline arrangement of the input and output shaft.
-

EV configurations (f)



C: Clutch
D: Differential
FG: Fixed gearing
GB: Gearbox
M: Electric motor

- By fully abandoning any mechanical gearing between the electric motor and the driving wheel, the out-rotor of a low-speed electric motor in the in-wheel drive can be directly connected to the driving wheel.
- The speed control of the electric motor is equivalent to the control of the wheel speed and hence the vehicle speed.
- However, this arrangement requires the electric motor to have a higher torque to start and accelerate the vehicle

Performance of Electric Vehicles

UNIT 3 Electric Vehicles: Syllabus

- Configurations of Electric vehicles,
- Performance of Electric vehicles:
  - Traction motor characteristics,
  - Tractive effort and transmission requirement:
    - **Gears,**
    - **Clutch,**
    - **Brakes,**
    - **Ideal gearbox,**
    - EV motor sizing,

    - Tractive effort in normal driving, Energy consumption.

Vehicle Performance Characteristics

- A vehicle's driving performance is usually evaluated by its
  - Acceleration time
  - Maximum speed, and
  - Gradeability.

Primary considerations of EV design to meet performance specification

  - Proper motor power rating and
  - Transmission parameters .

The design of all these parameters depends mostly on

  - Speed–power (torque) characteristics of the traction motor

Traction Motor Characteristics

- Let base speed is N
- At the low-speed region (Speed <N) , the motor has a constant torque.
- In the high-speed region (Speed >N), the motor has a constant power.
- This characteristic is usually represented by a speed ratio $x = \frac{Maximum\ speed}{Base\ Speed}$

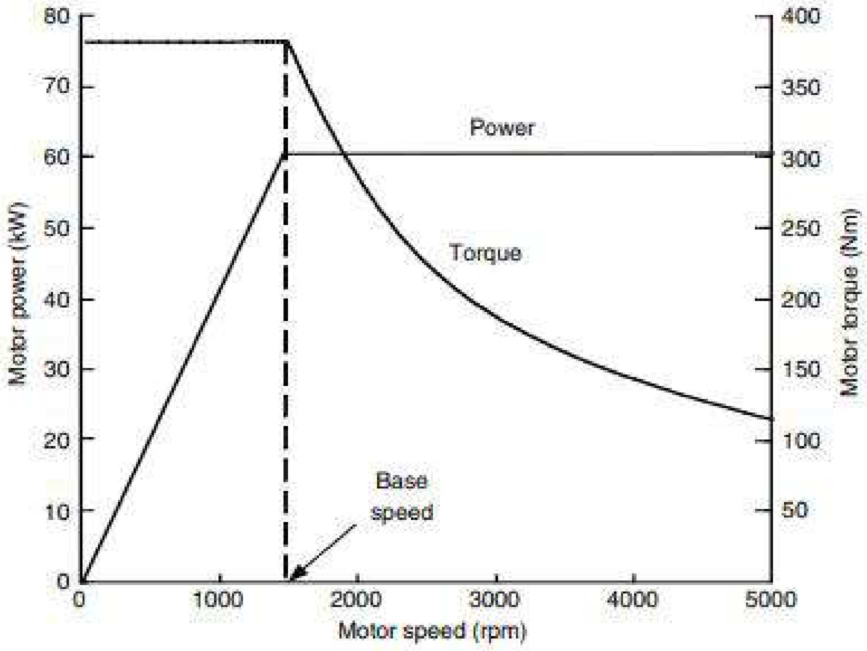


Fig: Typical variable-speed electric motor characteristics

In low-speed operations, **voltage supply to the motor increases with the increase of the speed** through the electronic converter while the flux is kept constant.

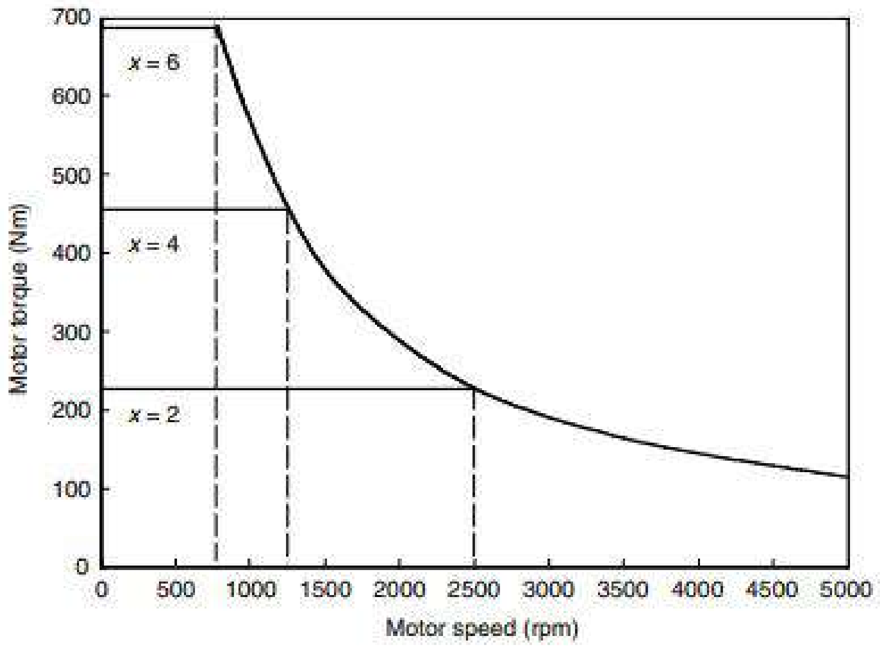
At the point of base speed, ***the voltage of the motor reaches the source voltage*****.**

After the base speed, the motor voltage is kept constant and the flux is weakened, dropping hyperbolically with increasing speed.

Hence, its torque also drops hyperbolically with increasing speed.

Example

- The Figure shows the torque–speed profiles of a 60 kW motor with different speed ratios x (x =2, 4, and 6).
- It is clear that with a long constant power region, the maximum torque of the motor can be significantly increased, and hence vehicle acceleration and Gradeability performance can be improved and the transmission can be simplified.
- However, each type of motor inherently has its limited maximum speed ratio.
- For example,
  - a permanent magnet motor has a small (x <2) because of the difficulty of field weakening due to the presence of the permanent magnet.
  - Switched reluctance motors may achieve x>6 and
  - Induction motors about x=4.



Speed–torque profile of a 60 kW electric motor with x = 2, 4, and 6

Tractive Effort and Transmission Requirement

- The tractive effort developed by a traction motor on driven wheels and the vehicle speed are expressed as

$$F_t = \frac{T_m i_g i_o \eta_t}{r_d}$$

and

$$V = \frac{\pi N_m r_d}{30 i_g i_o}$$

where

$T_m \rightarrow$ Motor Torque

$N_m \rightarrow$ Speed in rpm

$i_g \rightarrow$ gear ratio of transmission

$i_o \rightarrow$ gear ratio of final drive

$\eta_t \rightarrow$ efficiency of whole driveline from motor to driven wheels

$r_d \rightarrow$ Radius of drive wheels

Tractive Effort and Transmission Requirement

- The use of a multigear or single-gear transmission depends mostly on the motor speed–torque characteristics.
- That is, at a given rated motor power, if the motor has a long constant power region, a single-gear transmission would be sufficient for a high tractive effort at low speeds.
  Otherwise, a multigear (more than two gears) transmission has to be used.

Tractive Effort and Transmission Requirement

- Figure 1 shows the tractive effort of an EV, along with the vehicle speed with a traction motor of x=2 and a three-gear transmission.
- The first gear covers the speed region of a–b–c, the second gear covers d–e–f, and the third gear covers g–f–h.

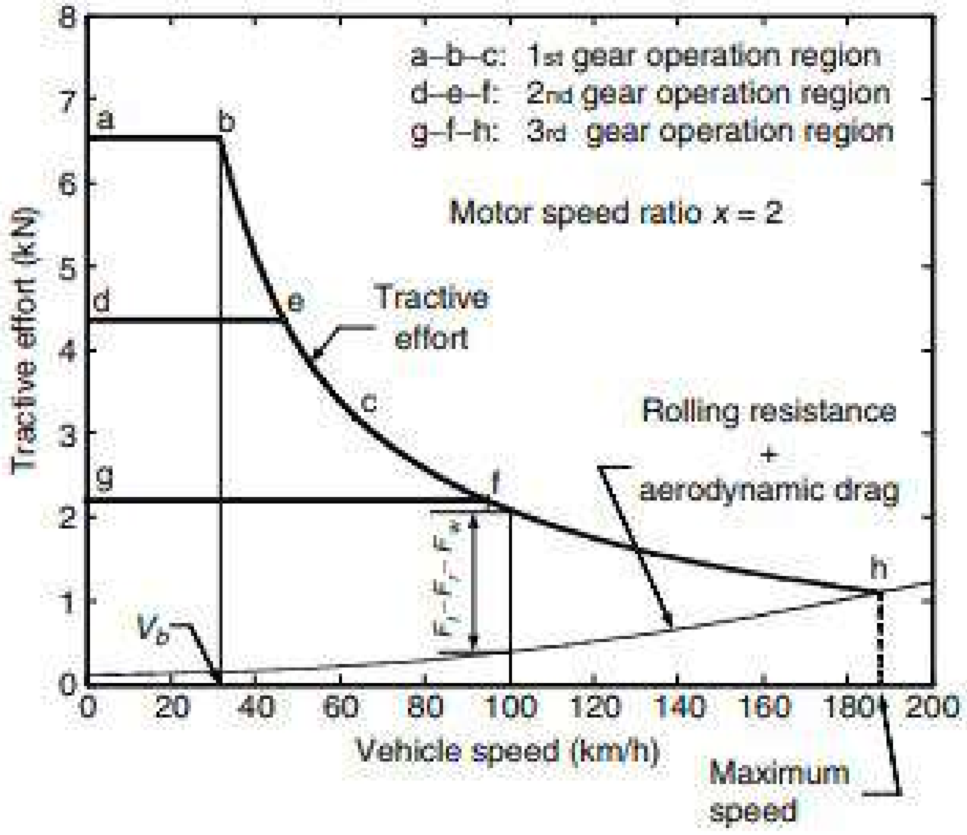


Fig1: Tractive effort vs. vehicle speed with a traction motor of x = 2 and three-gear transmission

Tractive Effort and Transmission Requirement

- Figure 2 shows the tractive effort with a traction motor of x=4 and a two-gear transmission.
- The first gear covers the speed region of a–b–c and the second gear d–e–f.

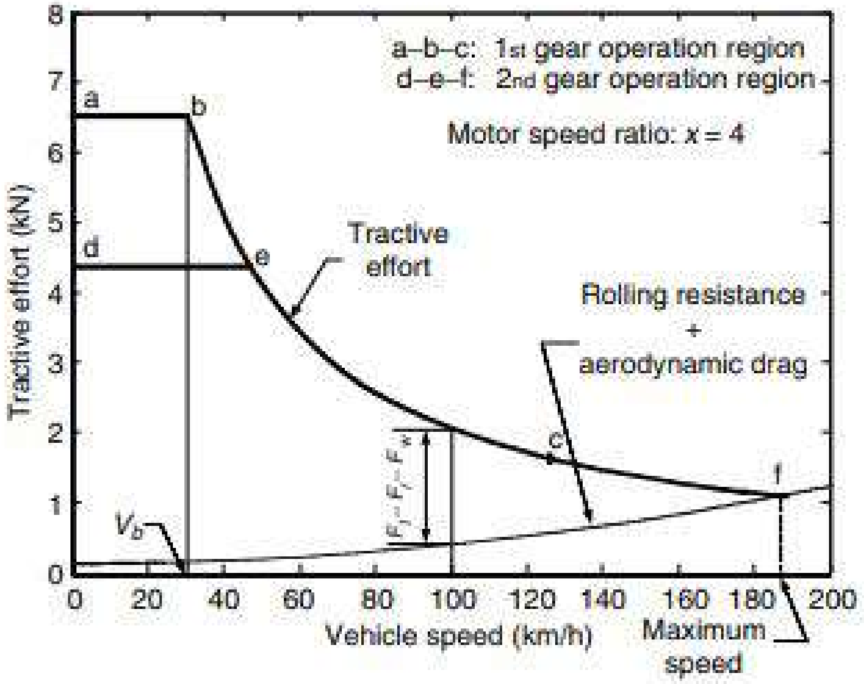


Fig2: Tractive effort vs. vehicle speed with a traction motor of x=4 and two-gear transmission

Tractive Effort and Transmission Requirement

- Figure 3 shows the tractive effort with a traction motor of x=6 and a single-gear transmission.
- These three designs have the same tractive effort vs. vehicle speed profiles.
- Therefore, the vehicles will have the same acceleration and gradeability performance

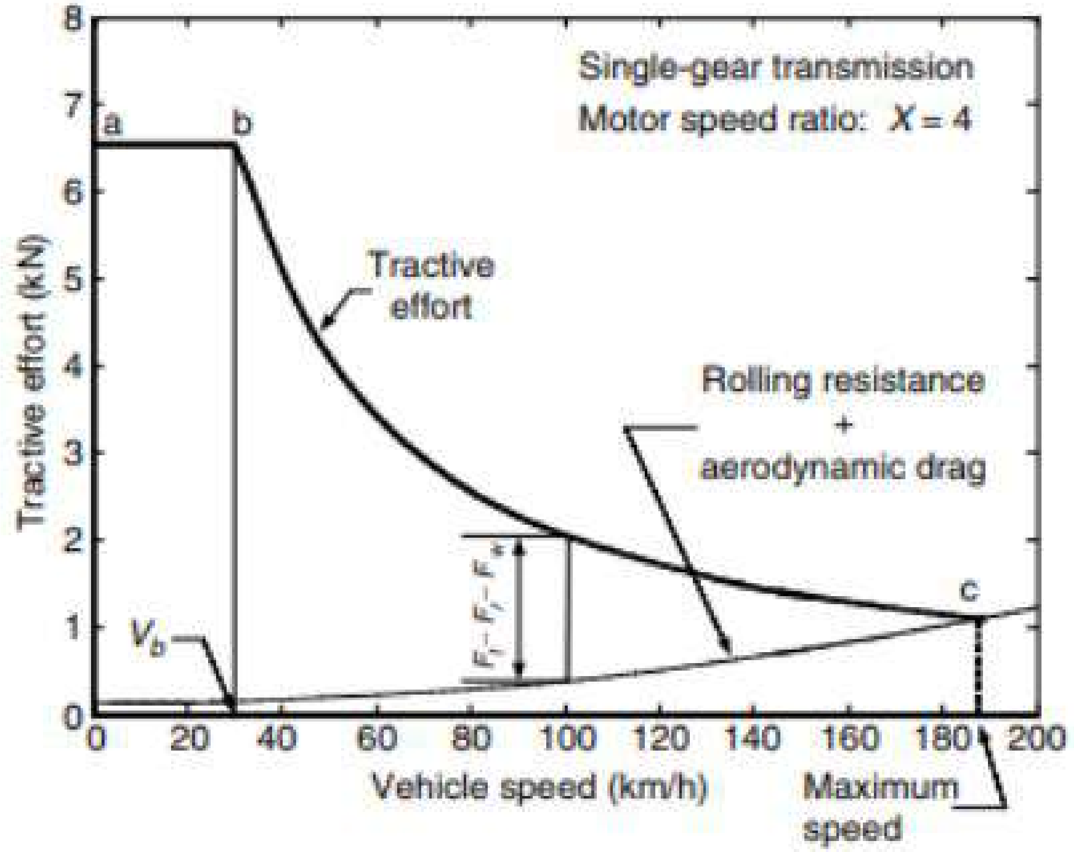
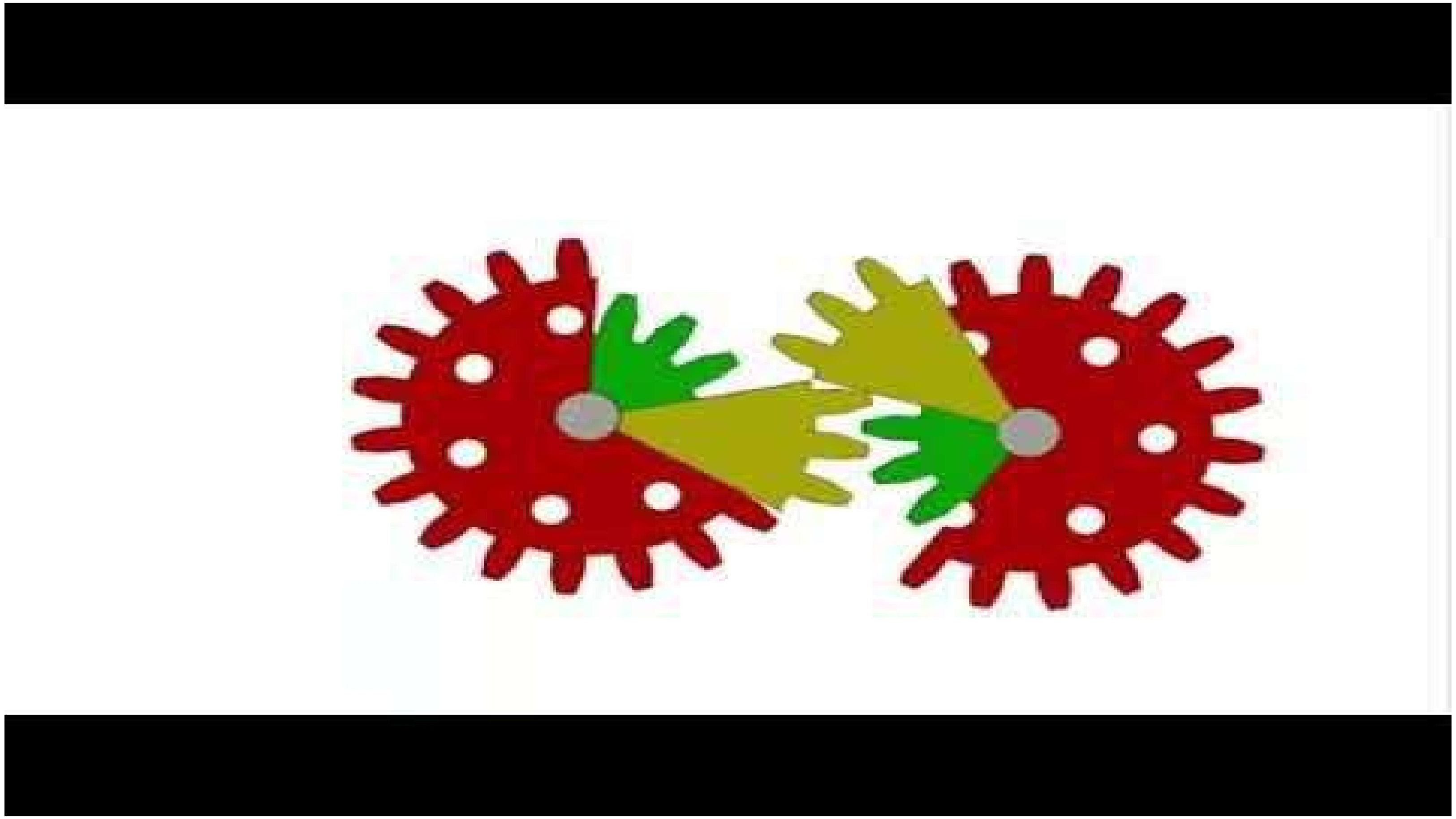


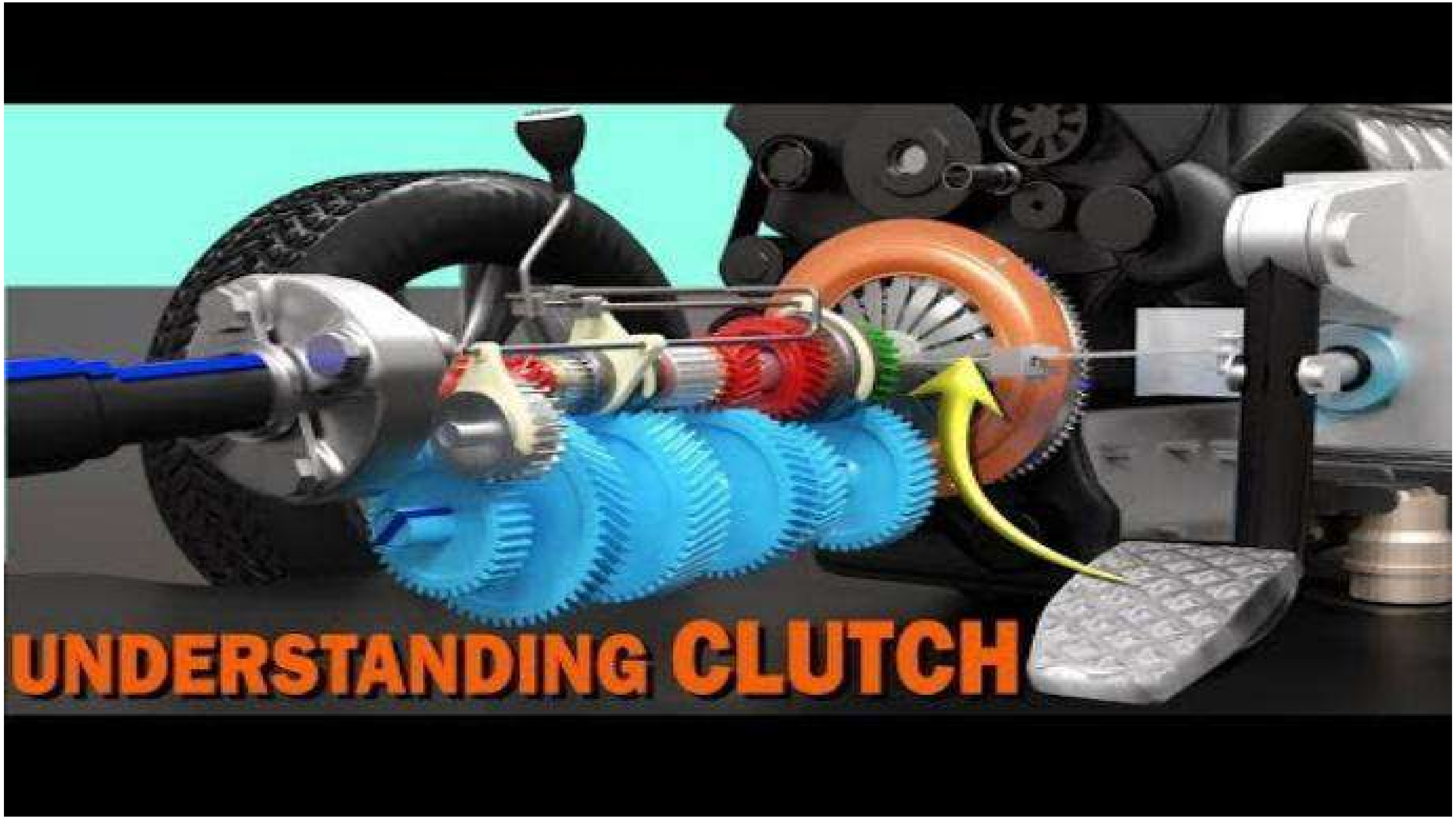
Fig3: Tractive effort vs. vehicle speed with a traction motor of x=6 and single-gear transmission

Gears

Mechanism: Gear Pair with Variable Speed



Working of Clutch



Working of Braking

Energy Consumption

- In transportation, the unit of energy is usually kilowatt-hour (kWh) rather than joule or kilojoule (J or kJ).
- The energy consumption per unit distance in kWh/km is generally used to evaluate the vehicle energy consumption.
- However, for ICE vehicles the commonly used unit is a physical unit of fuel volume per unit distance, such as liters per 100 km (l/100 km).
- In the U.S., the distance per unit volume of fuel is usually used; this is expressed as miles per gallon (mpg).
- On the other hand, for battery-powered EVs, the original energy consumption unit in kWh, measured at the battery terminals, is more suitable.
- The battery energy capacity is usually measured in kWh and the driving range per battery charge can be easily calculated.
- Similar to ICE vehicles, l/100 km (for liquid fuels) or kg/100 km (for gas fuels, such as hydrogen) or mpg, or miles per kilogram is a more suitable unit of measurement for vehicles that use gaseous fuels.

Energy Consumption

- Energy consumption is an integration of the power output at the battery terminals.
- For propelling, the battery power output is equal to resistance power and any power losses in the transmission and the motor drive, including power losses in electronics.
- The power losses in transmission and motor drive are represented by their efficiencies η_t and η_m, respectively.
- Thus, the battery power output can be expressed as

$$P_{b\text{-}out} = \frac{V}{\eta_t \eta_m}\left(M_v g (f_r + i) + \frac{1}{2}\rho_a C_D A_f V^2 + M\delta \frac{dV}{dt}\right).$$

Here, the non traction load (auxiliary load) is not included.
In some cases, the auxiliary loads may be too significant to be ignored and should be added to the traction load.
When regenerative braking is effective on an EV, a part of that braking energy — wasted in conventional vehicles — can be recovered by operating the motor drive as a generator and restoring it into the batteries.
The regenerative braking power at the battery terminals can also be expressed as

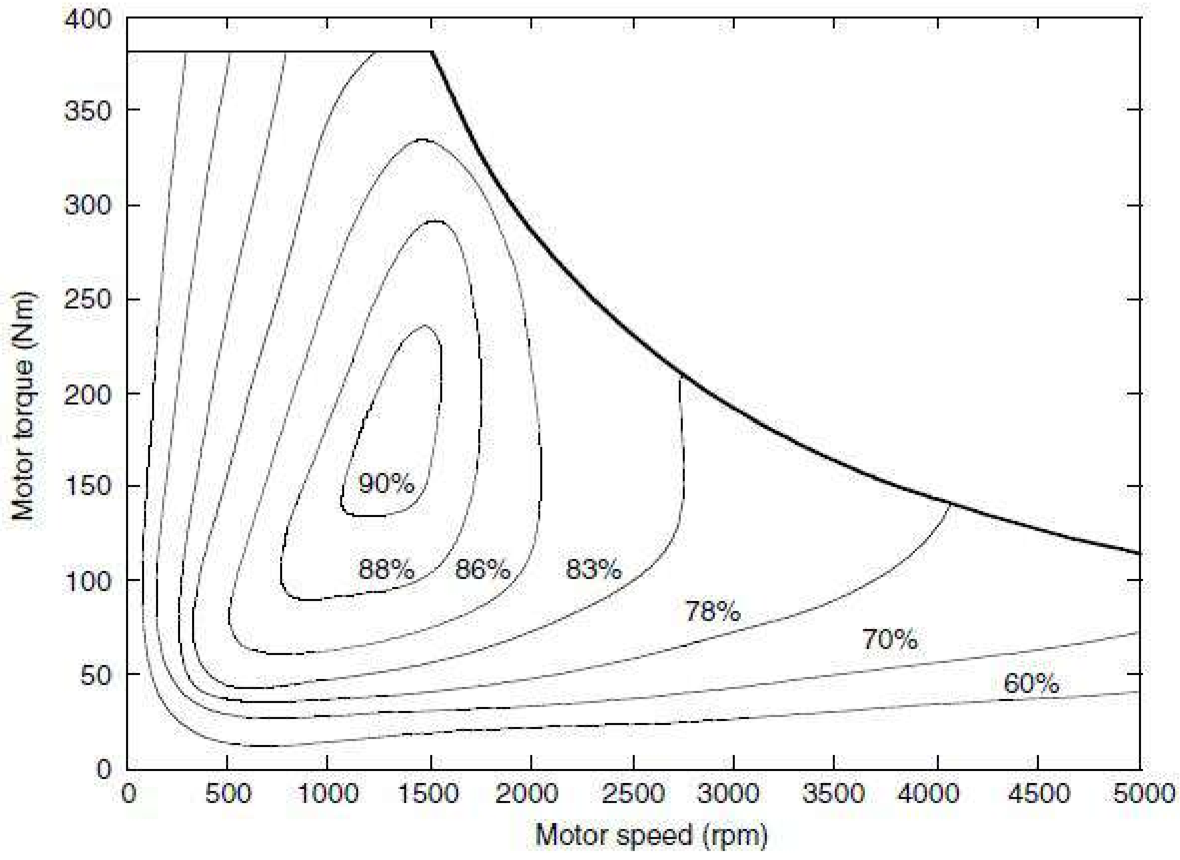
$$P_{b\text{-}in} = \frac{\alpha V}{\eta_t \eta_m}\left(M_v g (f_r + i) + \frac{1}{2}\rho_a C_D A_f V^2 + M\delta \frac{dV}{dt}\right),$$

Energy Consumption

- where road grade *i* or acceleration *dV/dt* or both of them are negative, and α (0< α< 1) is the percentage of the total braking energy that can be applied by the electric motor, called the regenerative braking factor.
- The regenerative braking factor α is a function of the applied braking strength and the design of the power train, which will be discussed in detail in the later chapters.
- The net energy consumption fro $E_{out} = \int_{traction} P_{b\text{-}out}\, dt + \int_{braking} P_{b\text{-}in}\, dt.$
- It should be noted that the braking power in (4.17) has a negative sign.
- When the net battery energy consumption reaches the total energy in the batteries, measured at their terminal, the batteries are empty and need to be charged.

Energy Consumption

- The traveling distance between two charges (usually called effective travel range) is determined by the total energy carried by the batteries, the resistance power, and the effectiveness of the regenerative braking (α).
- The efficiency of a traction motor varies with its operating points on the speed–torque (speed–power) plane as shown in Figure 4.14, where the most efficient operating area exists. In power train design, this area should overlap with or at least be as close as possible to the area of the greatest operation, as mentioned in the previous section.



Typical electric motor efficiency characteristic

III Year B.Tech. EEE II-Semester

Electric & Hybrid Vehicles

Course Code: PE116CW 3

(Professional Elective-II)

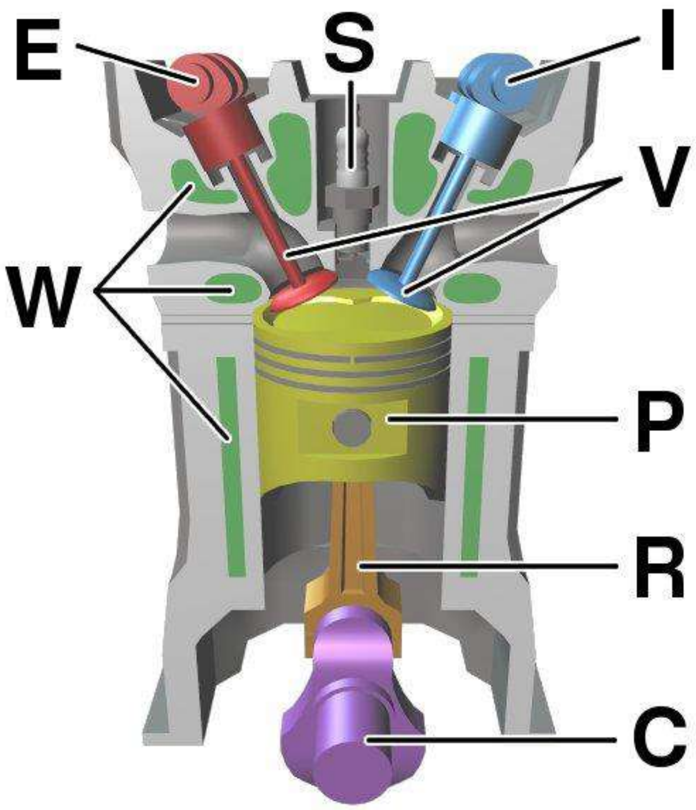
Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

UNIT 4: (~8 Lecture Hours)

- Hybrid Electric Vehicles: Internal combustion Engines,
- Concept of hybrid electric drive trains,
- Architectures of hybrid electric drive trains,
    - Series Hybrid electric drive trains,
    - Parallel Hybrid electric drive trains,
    - Series parallel Hybrid electric drive trains and
    - complex electric drive train.

Internal combustion Engines (**ICE** or **IC engine**)



- It is a heat engine in which the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit.
- In an ICE, the expansion of the high temperature and high-pressure gases produced by combustion applies direct force to some component of the engine.
- The force is typically applied to pistons (piston engine), turbine blades (gas turbine), a rotor(Wankel engine) , or a nozzle (jet engine).
- This force moves the component over a distance, transforming chemical energy into kinetic energy which is used to propel, move or power whatever the engine is attached to.
- This is replaced the external combustion engine for applications where the weight or size of an engine was more important.

- 4-stroke gasoline engine:
- **C** – crankshaft
- **E** – exhaust camshaft
- **I** – inlet camshaft
- **P** – piston
- **R** – connecting rod

- **S** – spark plug
- **V** – valves. red: exhaust, blue: intake.
- **W** – cooling water jacket
- *gray structure* – engine block

Concept of hybrid electric drive trains

Any vehicle power train is required to

(1) Develop sufficient power to meet the demands of vehicle performance

(2) Carry sufficient energy onboard to support vehicle driving in the given range

(3) Demonstrate high efficiency, and

(4) Emit No/less environmental pollutants.

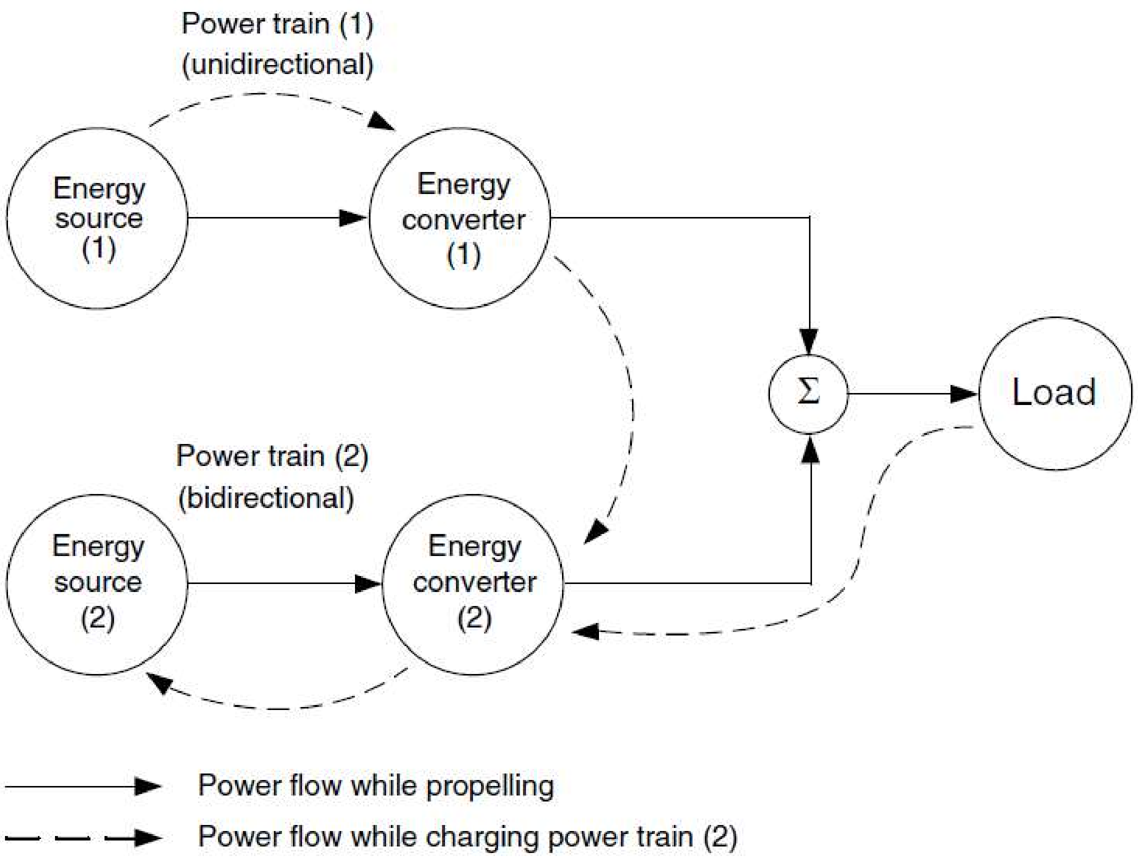
Concept of hybrid electric drive trains

If a vehicle have more than one energy source and energy converter (power source), such as a gasoline (or diesel) heat engine system, hydrogen–fuel cell–electric motor system, chemical battery–electric motor system, etc., is called hybrid drive train.

A vehicle that has two or more energy sources and energy converters is called a hybrid vehicle.

- A hybrid vehicle with an electrical power train (energy source energy converters) is called an HEV.
- A hybrid vehicle drive train usually consists of no more than two power trains.
- More than two power train configurations will complicate the system.
- For the purpose of recapturing part of the braking energy that is dissipated in the form of heat in conventional ICE vehicles, a hybrid drive train usually has a bidirectional energy source and converter. The other one is either bidirectional or unidirectional.

Conceptual illustration of a hybrid electric drive train



Hybrid drive trains supply the required power by an adapted power train.

Many available patterns of combining the power flows to meet load requirements are:

1. Power train 1 alone delivers power to the load
2. Power train 2 alone delivers power to the load
3. Both power train 1 and 2 deliver power to load at the same time
4. Power train 2 obtains power from load (regenerative braking)
5. Power train 2 obtains power from power train 1
6. Power train 2 obtains power from power train 1 and load at the same time
7. Power train 1 delivers power to load and to power train 2 at the same time
8. Power train 1 delivers power to power train 2, and power train 2 delivers power to load
9. Power train 1 delivers power to load, and load delivers power to power train 2.

Conceptual illustration of a hybrid electric drive train

- In the case of hybridization with a liquid fuel-IC engine (power train 1) and a battery-electric machine (power train 2)
- Pattern (1) is the engine-alone propelling mode. This may be used when the batteries are almost completely depleted and the engine has no remaining power to charge the batteries, or when the batteries have been fully charged and the engine is able to supply sufficient power to meet the power demands of the vehicle.
- Pattern (2) is the pure electric propelling mode, in which the engine is shut off. This pattern may be used in situations where the engine cannot operate effectively, such 0as very low speed, or in areas where emissions are strictly prohibited.
- Pattern (3) is the hybrid traction mode and may be used when a large amount of power is needed, such as during sharp acceleration or steep hill climbing.
- Pattern (4) is the regenerative braking mode, by which the kinetic or potential energy of the vehicle is recovered through the electric motor functioning as a generator. The recovered energy is stored in the batteries and reused later on.
- Pattern (5) is the mode in which the engine charges the batteries while the vehicle is at a standstill, coasting, or descending a slight grade, in which no power goes into or comes from the load.
- Pattern (6) is the mode in which both regenerative braking and the IC engine charge the batteries simultaneously.
- Pattern (7) is the mode in which the engine propels the vehicle and charges the batteries simultaneously.
- Pattern (8) is the mode in which the engine charges the batteries, and the batteries supply power to the load.
- Pattern (9) is the mode in which the power flows into the batteries from the heat engine through the vehicle mass.

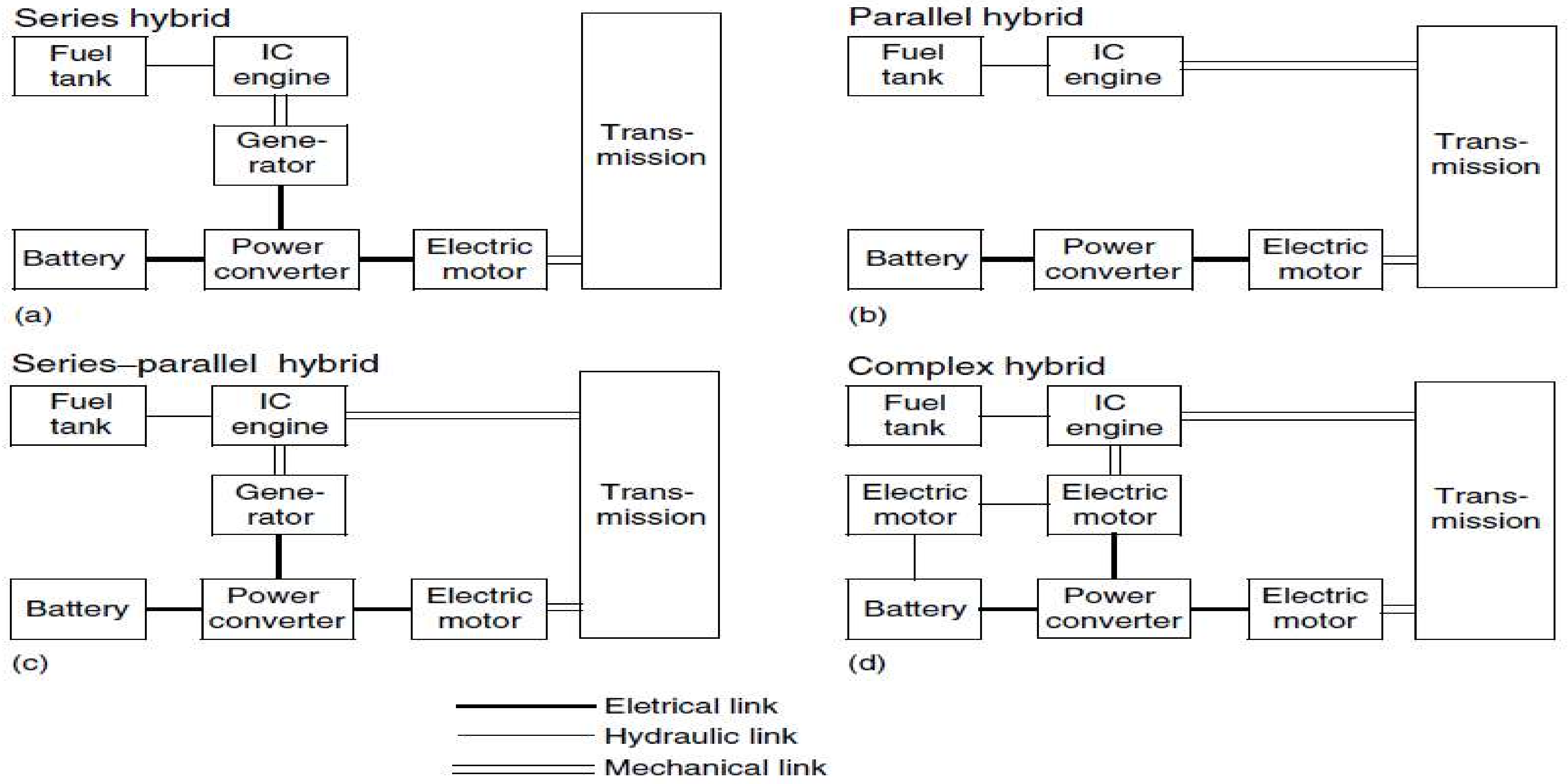
Concept of hybrid electric drive trains

- The varied operation modes in a hybrid vehicle create more flexibility over a single power train vehicle. With proper configuration and control, applying the specific mode for each special operating condition can optimize overall performance, efficiency, and emissions.
- However in a practical design, deciding which mode should be implemented depends on many factors, such as the physical configuration of the drive train, the power train efficiency characteristics, load characteristics, etc.
- Operating each power train in its optimal efficiency region is essential for the overall efficiency of the vehicle.

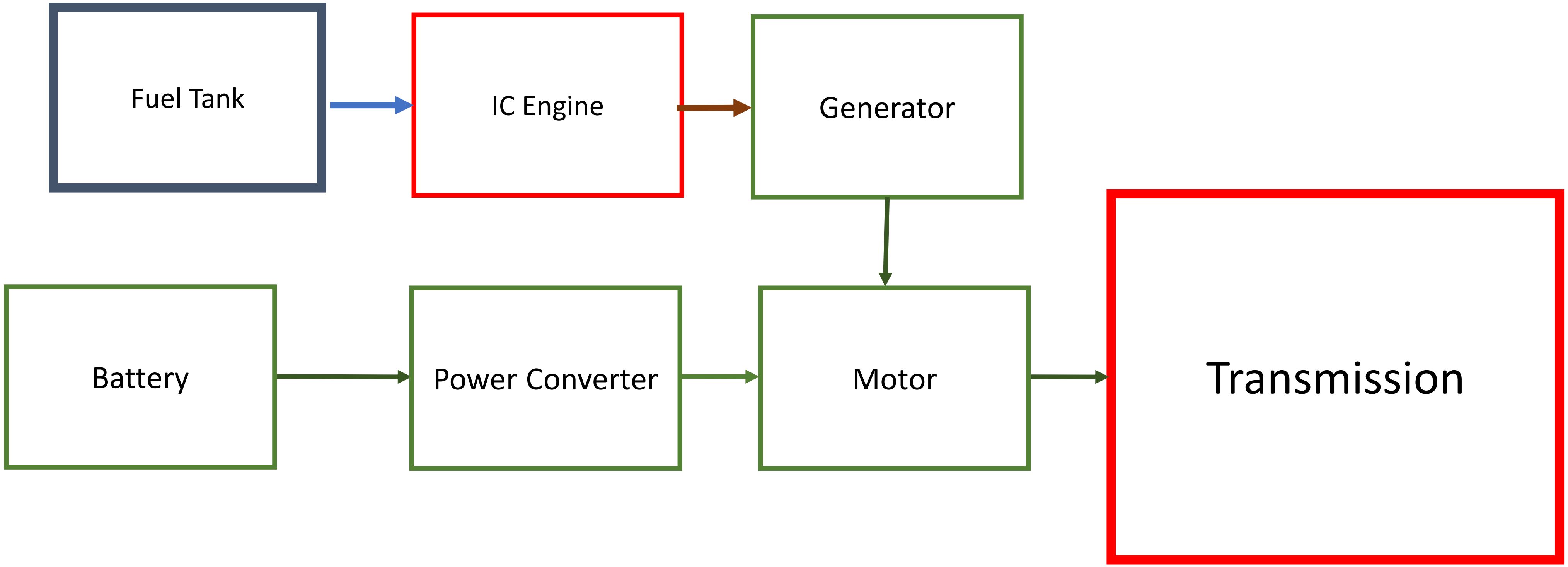
Concept of hybrid electric drive trains

- An IC engine generally has the best efficiency operating region with a wide throttle opening.
- On the other hand, efficiency suffering in an electric motor is not as detrimental when compared to an IC engine that operates away from its optimal region.
- The load power of a vehicle varies randomly in real operation due to frequent acceleration, deceleration, and climbing up and down grades.
- Actually, the load power is composed of two components: one is steady (average) power, which has a constant value, and the other is dynamic power, which has a zero average.
- In hybrid vehicle strategy, one power train that favors steady-state operation, such as an IC engine fuel cell, can be used to supply the average power.
- On the other hand, other power trains such as an electric motor can be used to supply the dynamic power.
- The total energy output from the dynamic power train will be zero in a whole driving cycle.
- This implies that the energy source of the dynamic power train does not lose energy capacity at the end of the driving cycle.
- It functions only as a power damper.
- In a hybrid vehicle, steady power may be provided by an IC engine, a Stirling engine, a fuel cell, etc.
- The IC engine or the fuel cell can be much smaller than that in a single power train design because the dynamic power is taken by the dynamic power source, and can then operate steadily in its most efficient region.
- The dynamic power may be provided by an electric motor powered by electrochemical batteries, ultracapacitors, flywheels (mechanical batteries), and their combinations.

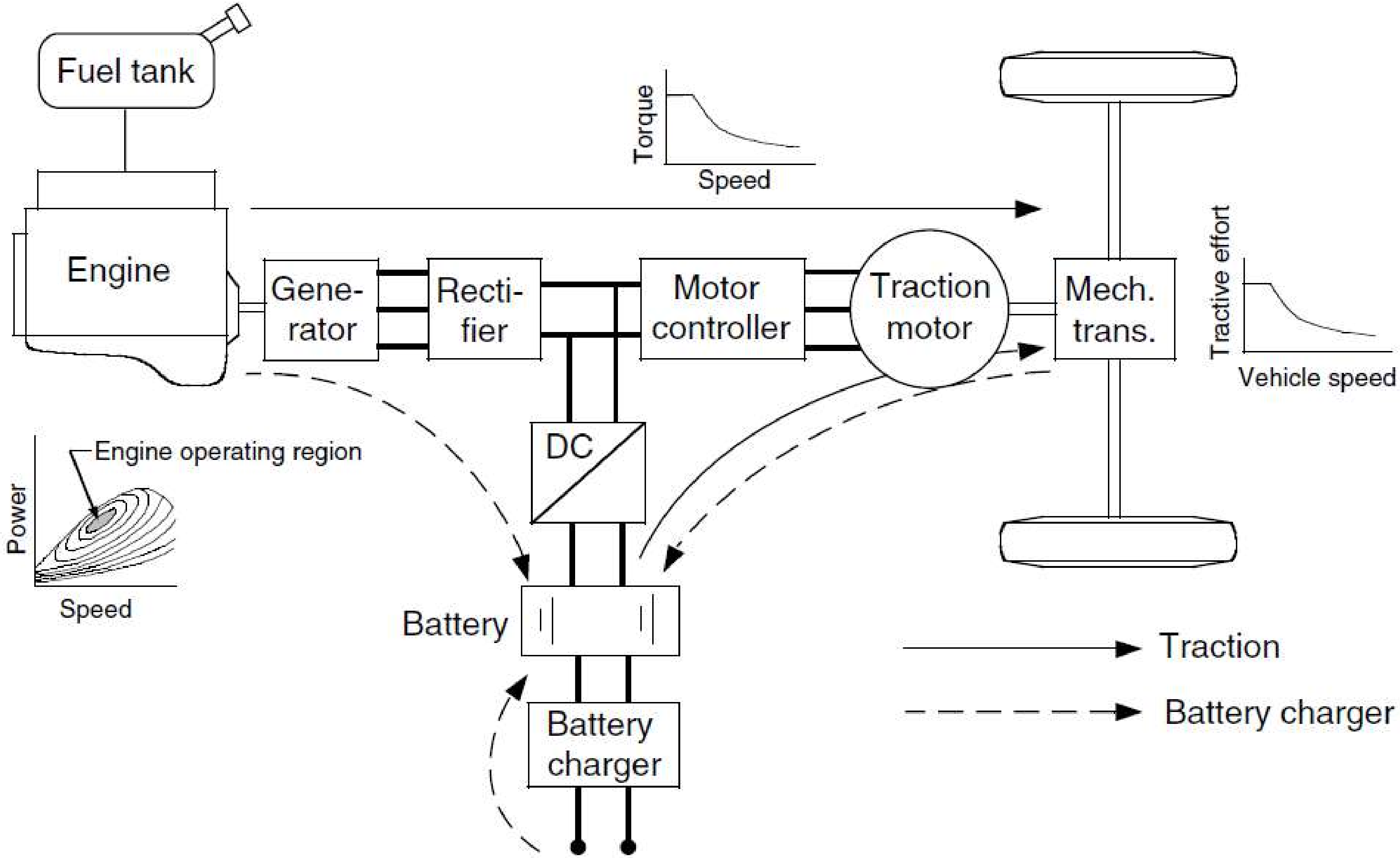
<u>Classification of hybrid electric vehicles</u>



Series Hybrid



Series Hybrid



Series Hybrid

1. Pure electric mode: The engine is turned off and the vehicle is propelled only by the batteries.
2. Pure engine mode: The vehicle traction power only comes from the engine-generator, while the batteries neither supply nor draw any power from the drive train. The electric machines serve as an electric transmission from the engine to the driven wheels.
3. Hybrid mode: The traction power is drawn from both the engine generator and the batteries.
4. Engine traction and battery charging mode: The engine-generator supplies power to charge the batteries and to propel the vehicle.
5. Regenerative braking mode: The engine-generator is turned off and the traction motor is operated as a generator. The power generated is used to charge the batteries.
6. Battery charging mode: The traction motor receives no power and the engine-generator charges the batteries.
7. Hybrid battery charging mode: Both the engine-generator and the traction motor operate as generators to charge the batteries.

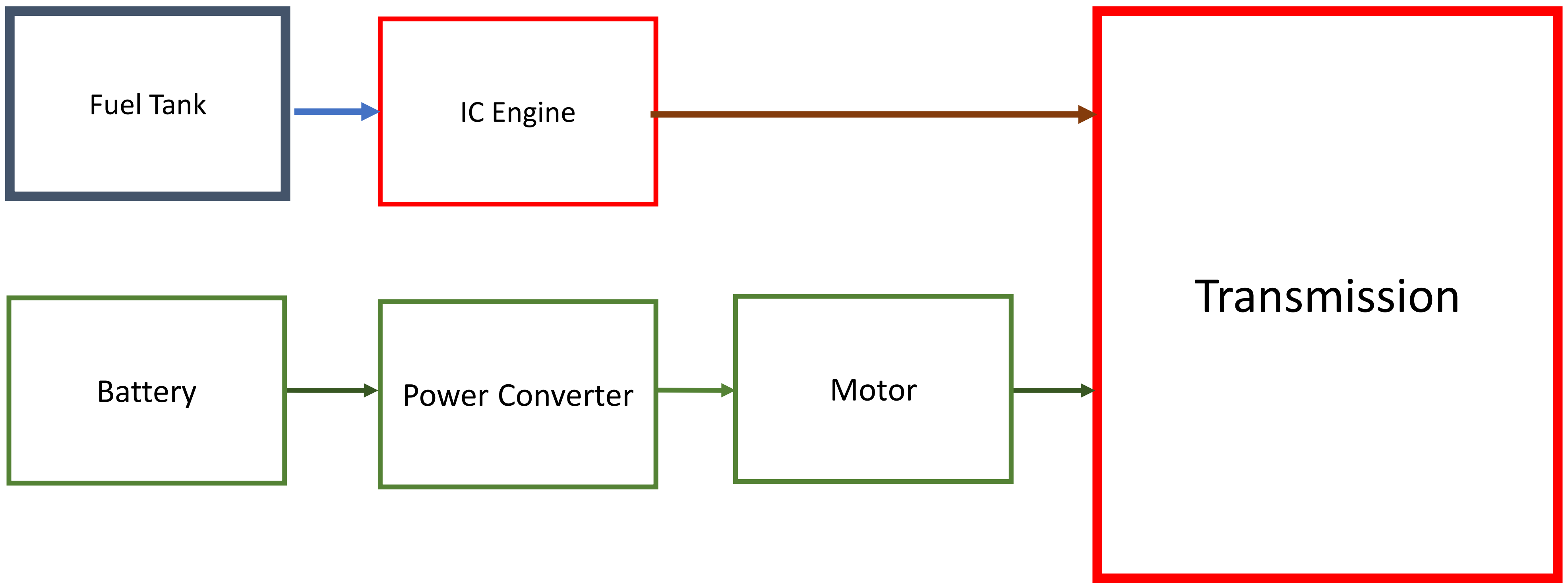
Series Hybrid Advantages

- The engine is fully mechanical when decoupled from the driven wheels. Therefore, it can be operated at any point on its speed–torque characteristic map, and can potentially be operated solely within its maximum efficiency region.
- The efficiency and emissions of the engine can be further improved by optimal design and control in this narrow region. A narrow region allows greater improvements than an optimization across the entire range.
- The mechanical decoupling of the engine from the driven wheels allows the use of a high-speed engine.
- As electric motors have near-ideal torque–speed characteristics, they do not need multi gear transmissions.
- Therefore, their construction is simple and the cost is less.
- Instead of using one motor and a differential gear, two motors may be used, each powering a single wheel. This provides speed decoupling between the two wheels like a differential but also acts as a limited slip differential for traction control purposes.
- The ultimate refinement would use four motors, thus making the vehicle an all-wheel-drive without the expense and complexity of differentials and drive shafts running through the frame.
- Simple control strategies may be used as a result of the mechanical decoupling provided by the electrical transmission.

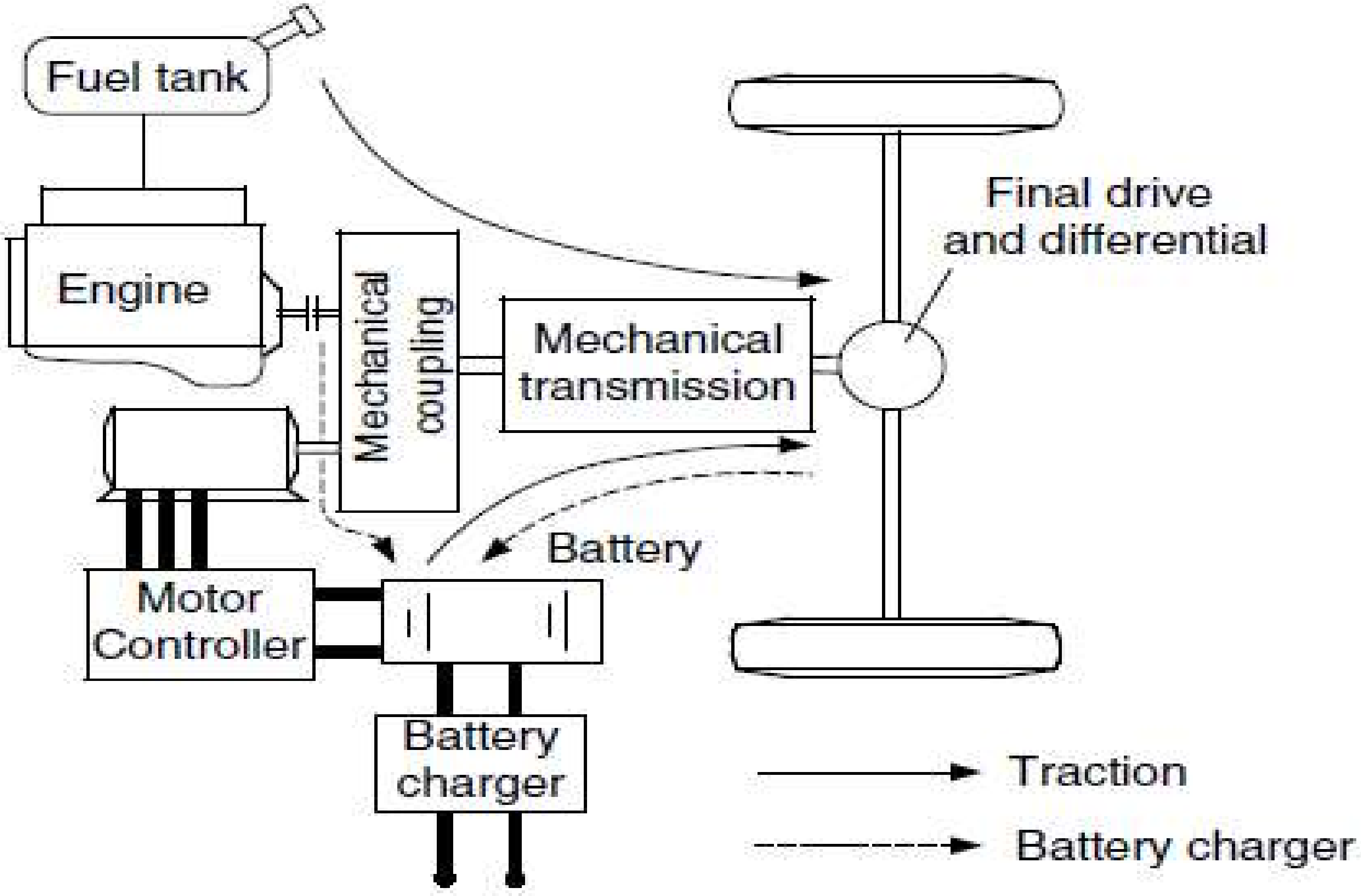
Series Hybrid disadvantages

1. The energy from the engine is converted twice (mechanical to electrical in the generator and electrical to mechanical in the traction motor). The inefficiencies of the generator and traction motor add up and the losses may be significant.
2. The generator adds additional weight and cost.
3. The traction motor must be sized to meet maximum requirements since it is the only powerplant propelling the vehicle.

Parallel Hybrid



Parallel Hybrid Electric drive train



- A parallel hybrid drive train is a drive train in which the engine supplies its power mechanically to the wheels like in a conventional ICE-powered vehicle.
- It is assisted by an electric motor that is mechanically coupled to the transmission.
- The powers of the engine and electric motor are coupled together by mechanical coupling.

Parallel Hybrid Electric drive train

1.Hybrid traction: When locks 1 and 2 are released the sun gear and ring gear can rotate and both the engine and electric machine supply positive speed and torque (positive power) to the driven wheels.

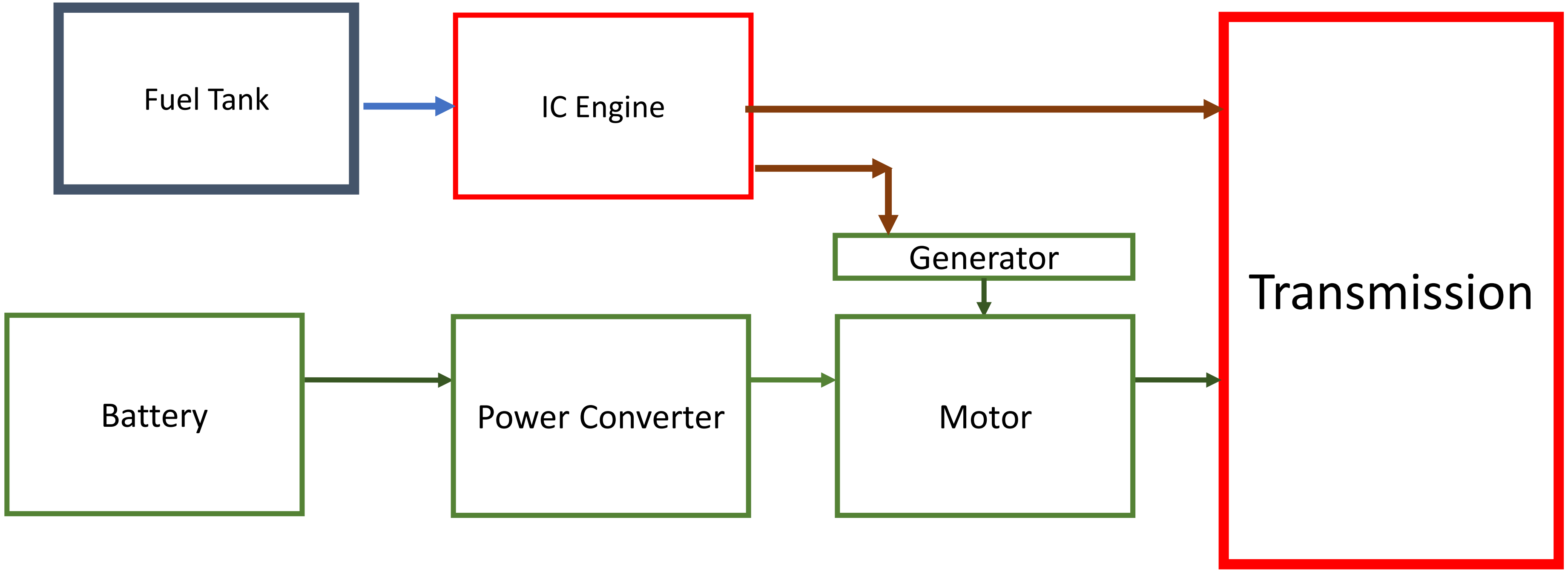
2. Engine-alone traction: When lock 2 locks the ring gear to the vehicle frame and lock 1 is released only the engine supplies power to the driven wheels.

3. Motor-alone traction: When lock 1 locks the sun gear to the vehicle frame (engine is shut off or clutch is disengaged) and lock 2 is released only the electric motor supplies its power to the driven wheels.

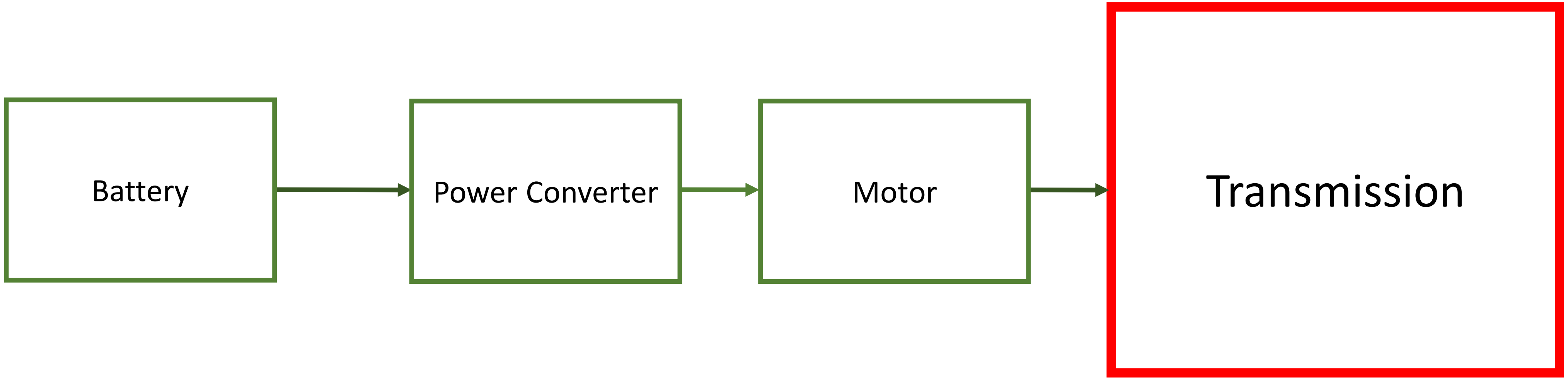
4. Regenerative braking: Lock 1 is set in locking state, the engine is shut off or clutch is disengaged, and the electric machine is controlled in regenerating operation (negative torque). The kinetic or potential energy of the vehicle can be absorbed by the electric system.

5. Battery charging from the engine: When the controller sets a negative speed for the electric machine, the electric machine absorbs energy from the engine.

Series & Parallel Hybrid



Electric Vehicle



III Year B.Tech. EEE II-Semester

Electric & Hybrid Vehicles

Course Code: PE116CW 3

(Professional Elective-II)

Prerequisites: Electrical Machines,
Power Electronics,
Control Systems.

Faculty: Gouthami Eragamreddy
Asst.Prof.
EEE, GNITS

UNIT 5: (~10 Lecture Hours)

- **Electric Propulsion Systems:**
  - 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.
- **Introduction to energy management strategies:** Regenerative braking.

Electric propulsion Systems

- Electric propulsion systems are at the heart of electric vehicles (EVs) and hybrid electric vehicles (HEVs).
- They are
  - Electric motors
  - Power converters
  - Electronic controllers.
- **Electric motor:** Converts the electric energy into mechanical energy to propel the vehicle, or, vice versa, to enable regenerative braking and/or to generate electricity for the purpose of charging the onboard energy storage.
- **Power converter:** Used to supply the electric motor with proper voltage and current.
- **Electronic controller:** This commands the power converter by providing control signals to it, and then controls the operation of the electric motor to produce proper torque and speed, according to the command from the drive.
- The electronic controller can be further divided into three functional units

1**) Sensor** (used to translate measurable quantities such as

current, voltage, temperature, speed, torque, and flux into electric signals through the interface circuitry)

2) **Interface circuitry** (signals are conditioned to the appropriate level before being fed into the processor.

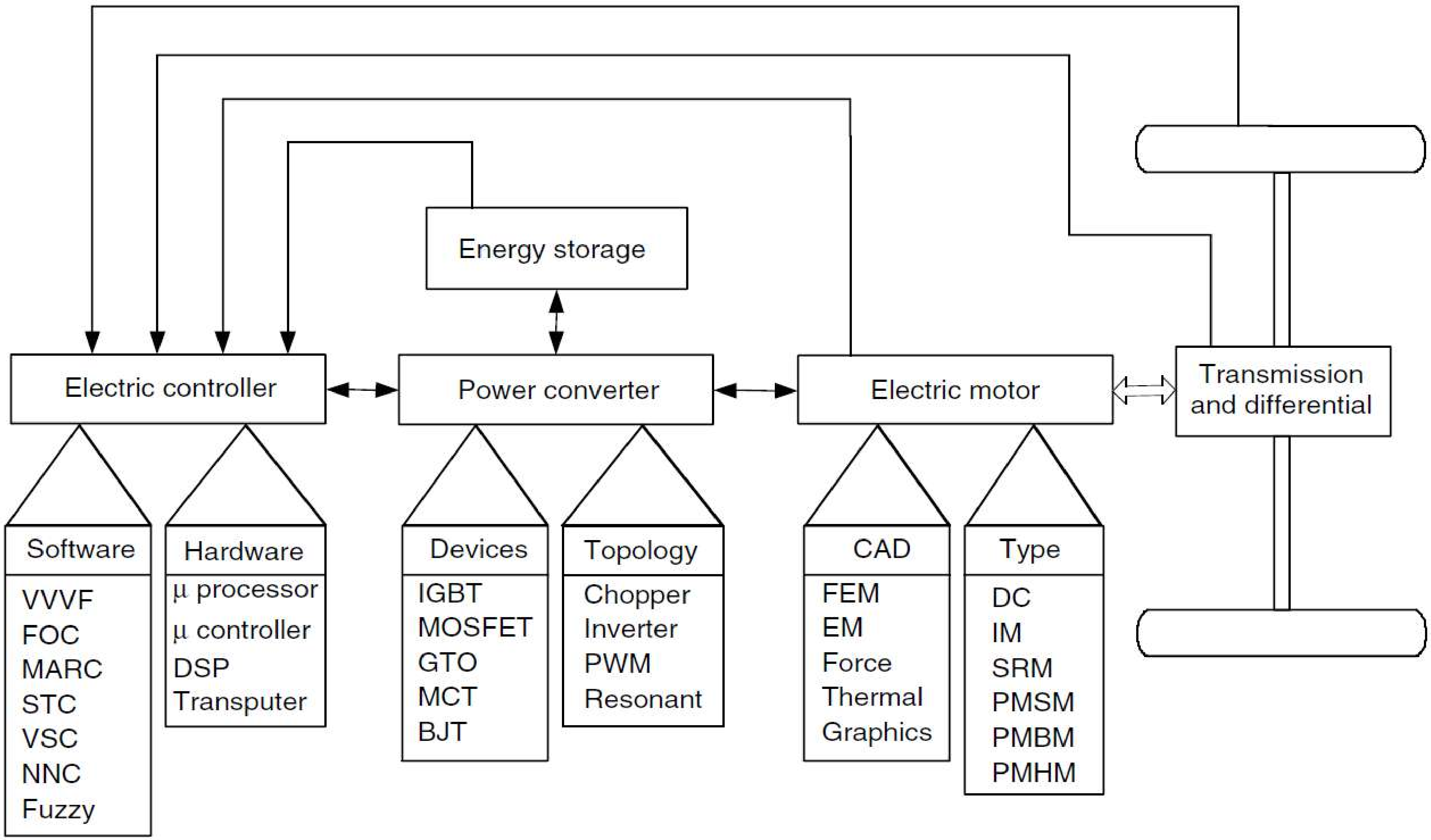
3) **Processor** (The processor output signals are usually amplified via the interface circuitry to drive power semiconductor devices of the power converter.)

Factors to choose electric propulsion systems for EVs and HEVs

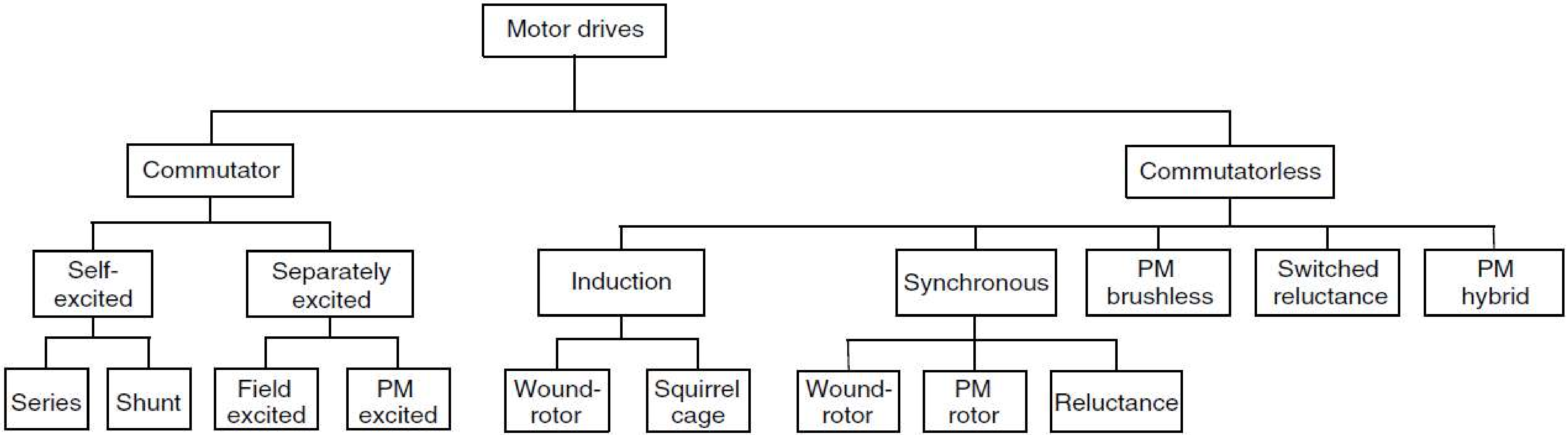
- Driver expectation
- Vehicle constraints
- Energy source

- **Driver expectation** is defined by a driving profile, which includes the acceleration, maximum speed, climbing capability, braking, and range.
- **Vehicle constraints** including volume and weight, depend on vehicle type, vehicle weight, and payload.
- **The energy source** relates to batteries, fuel cells, ultracapacitors, flywheels, and various hybrid sources.

Functional block diagram of a typical electric propulsion system



Classification of electric motor drives for EV and HEV applications



Electric motor drives for EV and HEV applications

- Motors used in EVs and HEVs require
  - Frequent starts and stops
  - High rates of acceleration/deceleration
  - High torque and low-speed hill climbing
  - Low torque and high-speed cruising
  - Very wide speed range of operation.
- The motor drives for EVs and HEVs can be classified into two main groups,

  Commutator motors and

  Commutator less motors

Electric motor drives for EV and HEV applications

- **Commutator motors:** (Traditional DC motors)
  - series excited
  - shunt excited
  - compound excited
  - separately excited
  - Permanent magnet (PM) excited motors.

  - DC motors need commutators and brushes to feed current into the armature, thus making them less reliable and unsuitable for maintenance-free operation and high speed.
  - Winding in DC motors have low specific power density.
  - Due to mature technology and simple control, DC motor drives have been prominent in electric propulsion systems.

Electric motor drives for EV and HEV applications

- Technological developments have recently pushed commutator less electric motors into a new era.
- Advantages include

  higher efficiency

  higher power density

  lower operating cost

  More reliable

  Maintenance free compared to commutator DC motors.

Thus, commutator less electric motors have now become more attractive.

Electric motor drives for EV and HEV applications

- Induction motors are widely accepted as a commutator less motor type for EV and HEV propulsion.
- This is because of their
  - Low cost
  - High reliability
  - Maintenance-free operation.
- However, conventional control of induction motors such as variable-voltage variable-frequency (VVVF) cannot provide the desired performance.
- With the advent of the power electronics and microcomputer era, the principle of field-oriented control (FOC) or vector control of induction motors has been accepted to overcome their control complexity due to their nonlinearity.
- However, these EV and HEV motors using FOC still suffer from low efficiency at low light loads and limited constant-power operating range.
- By replacing the field winding of conventional synchronous motors with PMs, PM synchronous motors can eliminate conventional brushes, slip rings, and field copper losses.

Electric motor drives for EV and HEV applications

- PM synchronous motors are also called PM brushless AC motors, or sinusoidal-fed PM brushless motors, because of their sinusoidal AC current and brushless configuration.
- Since these motors are essentially synchronous motors, they can run from a sinusoidal or pulsed waveform modulation supply (PWM supply) without electronic commutation.
- When PMs are mounted on the rotor surface, they behave as non salient synchronous motors because the permeability of PMs is similar to that of air.
- By burying those PMs inside the magnetic circuit of the rotor, the saliency causes an additional reluctance torque, which leads to facilitating a wider speed range at constant power operation.
- On the other hand, by abandoning the field winding or PMs while purposely making use of the rotor saliency, synchronous reluctance motors are generated.
- These motors are generally simple and inexpensive, but with relatively low output power.
- Similar to induction motors, these PM synchronous motors usually use FOC for high-performance applications.
- Because of their inherently high power density and high efficiency, they have been accepted as having great potential to compete with induction motors for EV and HEV applications.

Electric motor drives for EV and HEV applications

- By virtually inverting the stator and rotor of PM DC motors (commutator), PM brushless DC motors are generated.
- It should be noted that the term "DC" may be misleading, since it does not refer to a DC current motor. Actually, these motors are fed by rectangular AC current, and are hence also known as rectangular-fed PM brushless motors. The most obvious advantage of these motors is the removal of brushes.
- Another advantage is the ability to produce a large torque because of the rectangular interaction between current and flux.
- Moreover, the brushless configuration allows more cross sectional area for the armature windings.
- Since the conduction of heat through the frame is improved, an increase in electric loading causes higher power density.
- Different from PM synchronous motors, these PM brushless DC motors generally operate with shaft position sensors.
- Recently, sensor less control technologies have been developed in the Power Electronics and Motor Drive Laboratory at Texas A&M University.

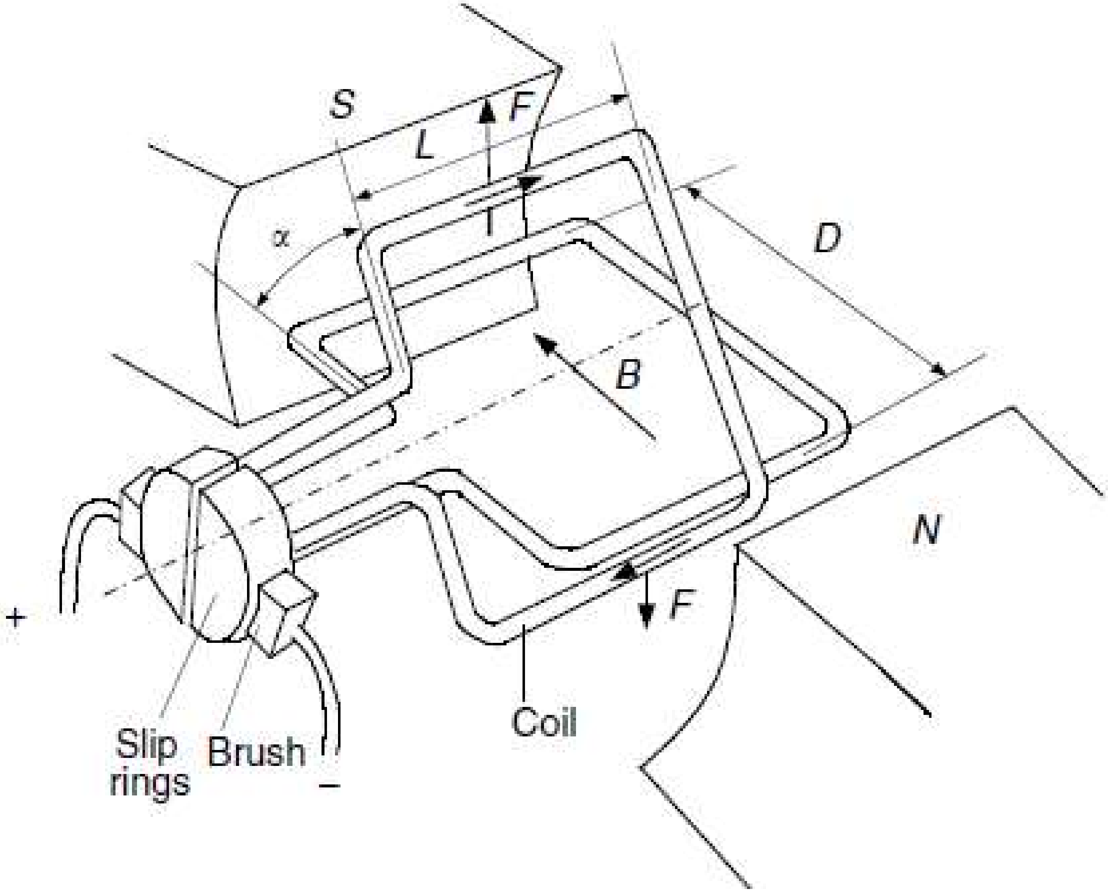
Electric motor drives for EV and HEV applications

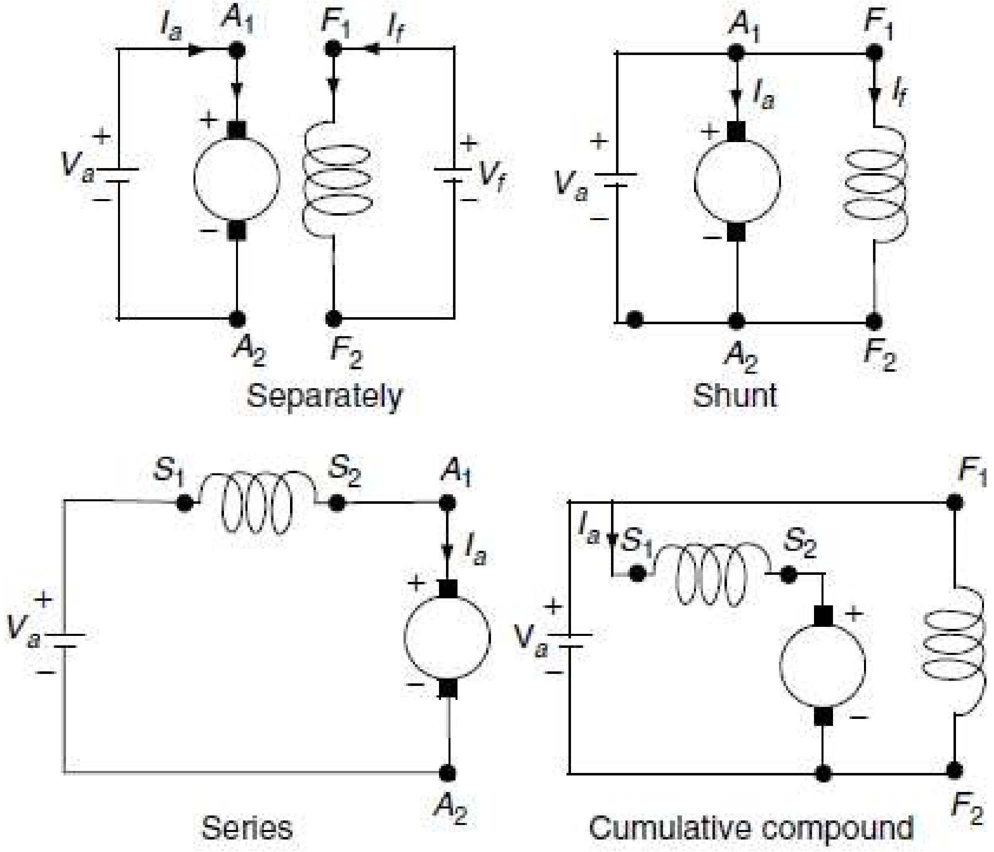
- Switched reluctance (SR) motors have been recognized to have considerable potential for EV and HEV applications.
- Basically, they are direct derivatives of single-stack variable-reluctance stepping motors.
- SR motors have the definite advantages of simple construction, low manufacturing cost, and outstanding torque–speed characteristics for EV and HEV applications.
- Although they possess simplicity in construction, this does not imply any simplicity of their design and control.
- Because of the heavy saturation of pole tips and the fringe effect of pole and slots, their design and control are difficult and subtle.
- Traditionally, SR motors operate with shaft sensors to detect the relative position of the rotor to the stator.
- These sensors are usually vulnerable to mechanical shock and sensitive to temperature and dust.
- Therefore, the presence of the position sensor reduces the reliability of SR motors and constrains some applications.
- Recently, sensor less technologies have been developed in the Power Electronics and Motor Drive Laboratory — again at Texas A&M University.
- These technologies can ensure smooth operation from zero speed to maximum speed.

Configuration and control of DC motor drives

- DC motor drives have been widely used in applications requiring
  - Adjustable speed
  - Good speed regulation,
  - Frequent starting
  - Braking and
  - Reversing.
- DC motor drives are used in electric traction applications because of their
  - technological maturity and
  - control simplicity

DC Motor


S
F
L
I
α
D
B
N
F
+
Slip rings
Brush
Coil
–


I_a
A_1
F_1
I_f
V_a
V_f
A_2
F_2
Separately
Shunt
S_1
S_2
Series
Cumulative compound

DC Motor

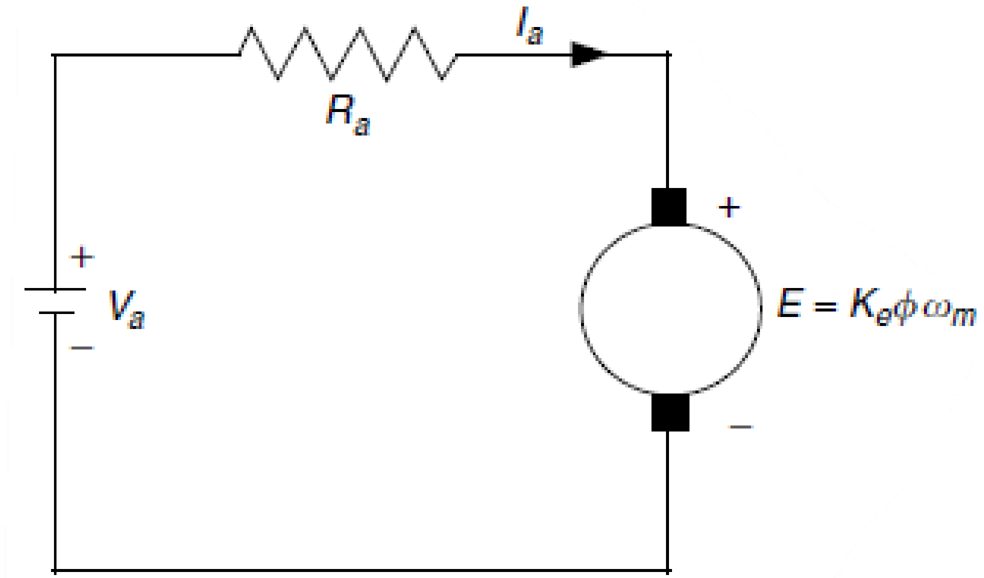
- Operation Principle: When a wire carrying electric current is placed in a magnetic field, a magnetic force acting on the wire is produced.

$$F = BIL$$

$$T = BIL \cos\alpha$$

DC Motors are described by armature voltage back electromotive force and field flux.

DC Motor steady state equivalent circuit



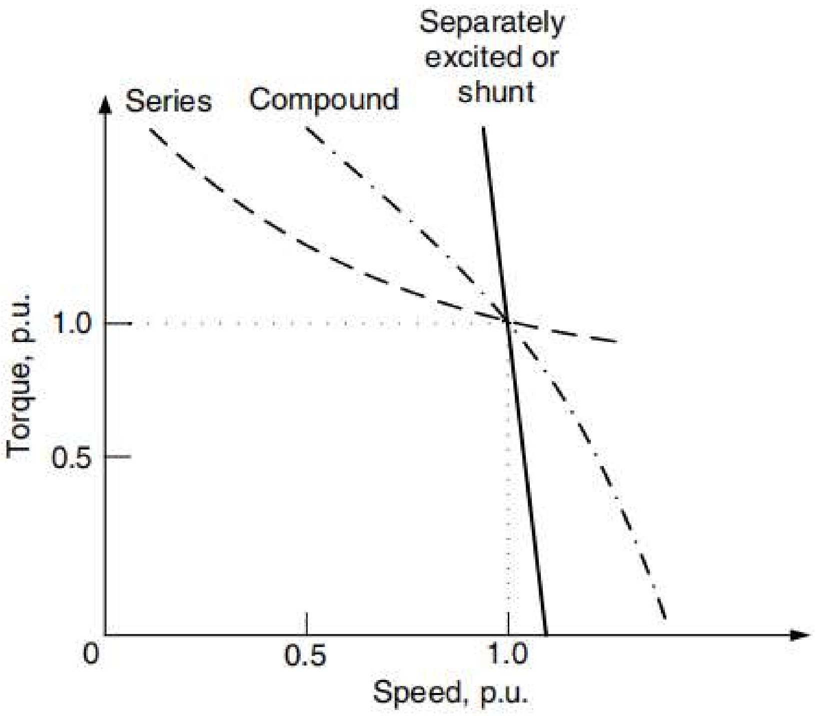
Steady-state equivalent circuit of the armature circuit of a DC motor

$$V_a = E + R_a I_a$$
$$E = K_e \phi\, \omega_m$$
$$T = K_e \phi\, I_a$$
$$T = \frac{K_e \phi}{R_a} V - \frac{(K_e \phi)^2}{R_a} \omega_m$$
$$\Phi = K_f I_a$$

Where

- ϕ is the flux per pole in Weber,
- I_a is the armature current in A,
- V_a is the armature voltage in volts.
- R_a is the resistance of the armature circuit in ohms,
- ω_m is the speed of the armature in rad/sec,
- T is the torque developed by the motor in Nm,
  K_e *is constant*.

Speed Characteristics of DC Motors



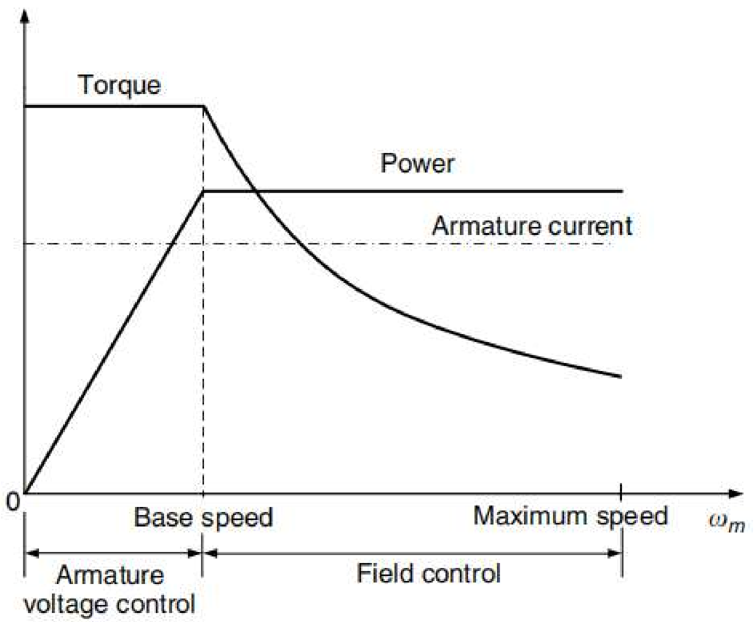
$$T = \frac{K_e K_f V_a^2}{(R_a + K_e K_f \omega_m)^2},$$

In the case of series:

- Any increase in torque is accompanied by an increase in the armature current and, therefore, an increase in magnetic flux.
- Because flux increases with the torque, the speed drops to maintain a balance between the induced voltage and the supply voltage. The characteristic, therefore, shows a dramatic drop.
- A motor of standard design works at the knee point of the magnetization curve at the rated torque.
- At heavy torque (large current) overload, the magnetic circuit saturates and the speed–torque curve approaches a straight line.
- Series DC motors are suitable for applications requiring high starting torque and heavy torque overload, such as traction.
- This was just the case for electric traction before the power electronics and microcontrol era.
- **Disadvantages:** They are not allowed to operate without load torque with full supply voltage. Otherwise, their speed will quickly increase up to a very high value

Combined Armature Voltage and Field Control

- The independence of armature voltage and field provides more flexible control of the speed and torque than other types of DC motors.
- In EV and HEV applications, the most desirable speed–torque characteristic is to have a constant torque below a certain speed (base speed), with the torque dropping parabolically with the increase of speed (constant power) in the range above the base speed,
- In the range of lower than base speed,the armature current and field are set at their rated values, producing the rated torque.
- From equations, it is clear that the armature voltage must be increased proportionally with the increase of the speed.
- At the base speed, the armature voltage reaches its rated value (equal to the source voltage) and cannot be increased further.
- In order to further increase the speed, the field must be weakened with the increase of the speed, and then the back EMF E and armature current must be maintained constant.
- The torque produced drops parabolically with the increase in the speed and the output power remains constant.



$$V_a = E + R_a I_a$$

$$E = K_e \phi \, \omega_m$$

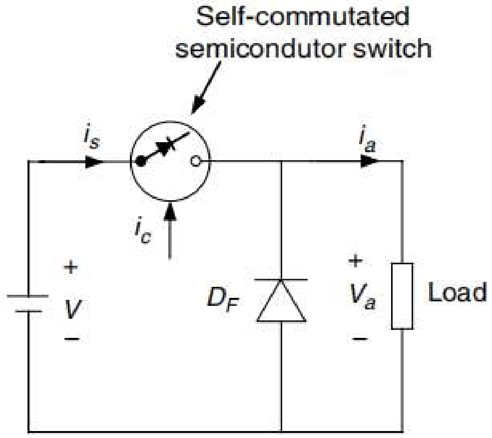
$$T = K_e \phi \, I_a$$

Control of DC Motors

- Choper Control of DC Motors
- Multiquadrant Control of Chopper fed DC Motor Drives
  - Two quadrant control of forward motoring and regenerative braking
  - Four Quadrant Operation

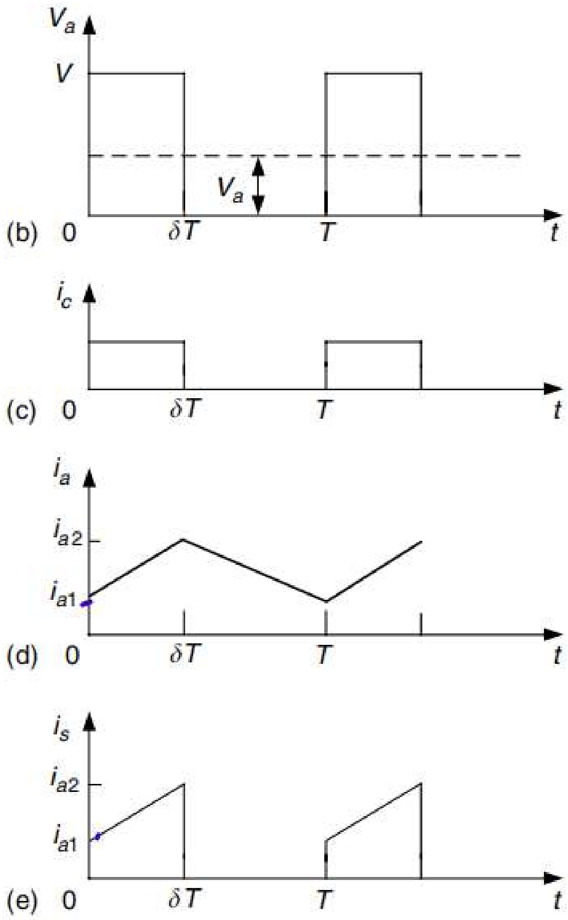
Chopper Control of DC Motors

- Advantages of using Choppers in controlling DC motors is
- high efficiency
- flexibility in control
- light weight
- small size
- Quick response, and
- regeneration down to very low speeds.



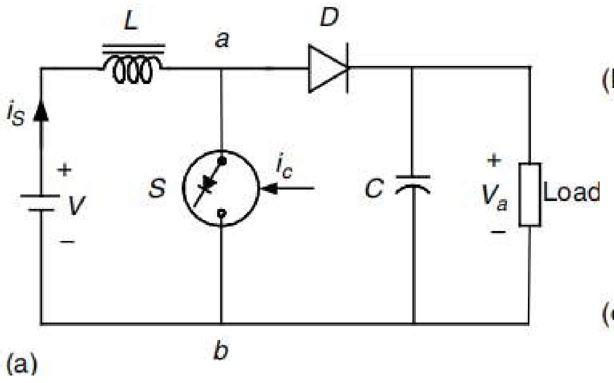
Presently,

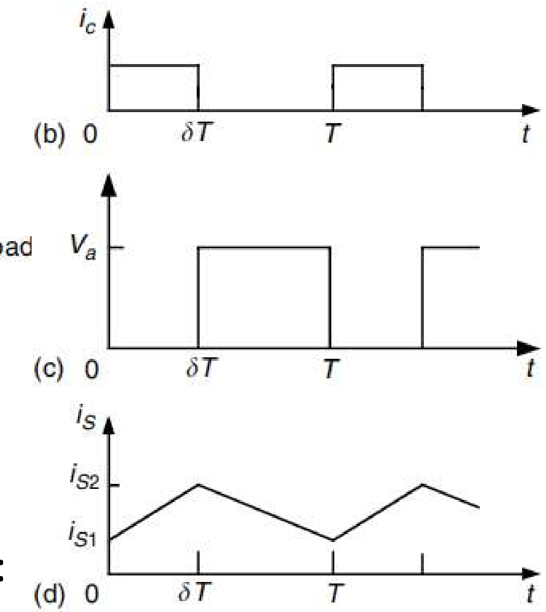
- the separately excited DC motors are usually used in traction, due to the control flexibility of armature voltage and field.
- For a DC motor control in open-loop and closed-loop configurations, the chopper offers a number of advantages due to its high operation frequency.
- High operation frequency results in high-frequency output voltage ripple and, therefore, less ripples in the motor armature current and a smaller
- region of discontinuous conduction in the speed–torque plane.
- A reduction in the armature current ripple reduces the armature losses. A reduction or elimination of the discontinuous conduction region improves speed regulation and the transient response of the drive.



Principle of operation of a step down (or class A) chopper: (a) basic chopper circuit; (b) to (e) waveforms

Chopper Control of DC Motors: Step up chopper or Class B chopper





Principle of operation of a step-up (or class B) chopper: (a) basic chopper circuit; (b) to (d) waveforms

The presence of control signal i_c indicates the duration for which the switch can conduct if forward-biased.

- **During a chopping period T**,
  - It remains closed for an interval $\mathbf{0 \leq t \leq \delta T}$ and
  - Remains open for an interval $\mathbf{\delta T \leq t \leq T}$.
- During the on period, i_S increases from i_{S1} to i_{S2}, thus increasing the magnitude of energy stored in inductance L.
- When the switch is opened, current flows through the parallel combination of the load and capacitor C.
- Since the current is forced against the higher voltage, the rate of change of the current is negative.
- It decreases from i_{S2} to i_{S1} in the switch's off period.
- The energy stored in the inductance L and the energy supplied by the low-voltage source are given to the load.

The capacitor C serves two purposes.

At the instant of opening of switch S, the source current, i_S, and load current, i_a, are not the same.

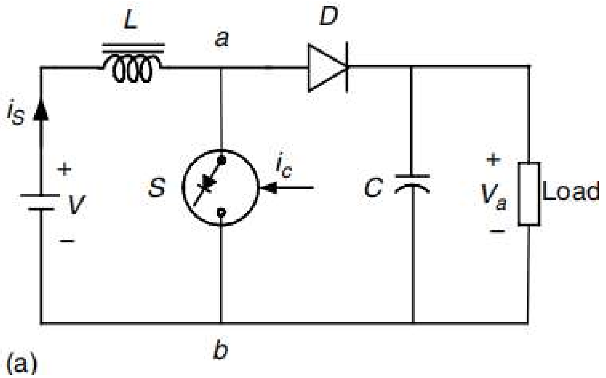
In the absence of C, the turn off of S will force the two currents to have the same values.

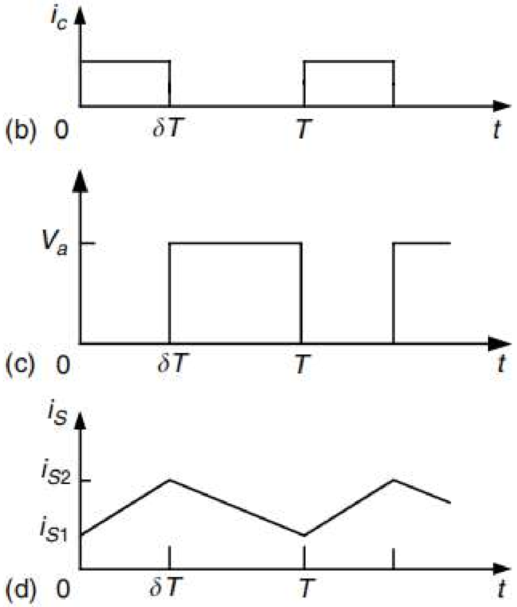
This will cause high induced voltage in the inductance L and the load inductance.

Another reason for using capacitor C is to reduce the load voltage ripple.

The purpose of the diode D is to prevent any flow of current from the load into switch S or source V

Chopper Control of DC Motors: Step up chopper or Class B chopper





Principle of operation of a step-up (or class B) chopper: (a) basic chopper circuit; (b) to (d) waveforms

The average voltage across the terminal a, b is given as

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

The average voltage across the inductance L is

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

The source voltage is $V = V_L + V_{ab}$

The output voltage Va can be changed from V to ∞ by controlling δ from 0 to 1.

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

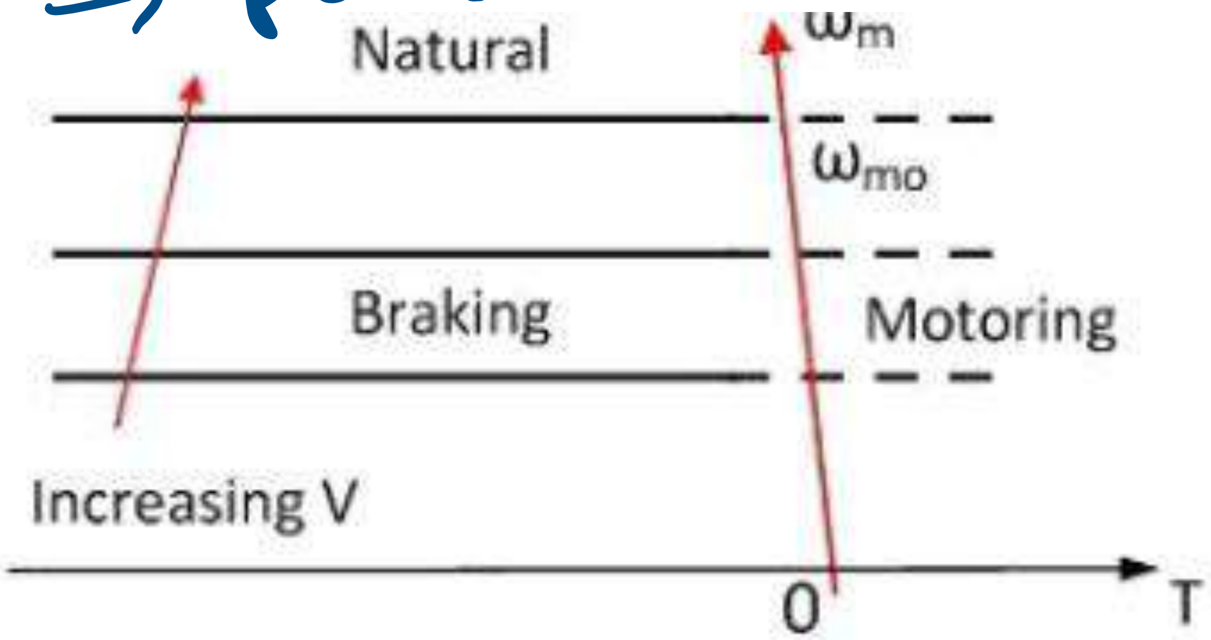
The main advantage of a step-up chopper is the low ripple in the source current.

While most applications require a step-down chopper, the step-up chopper finds application in low-power battery-driven vehicles.

The principle of the step-up chopper is also used in the regenerative braking of DC motor drives.

Braking

: → Regen. braking
→ Dynamic braking
→ plugging.



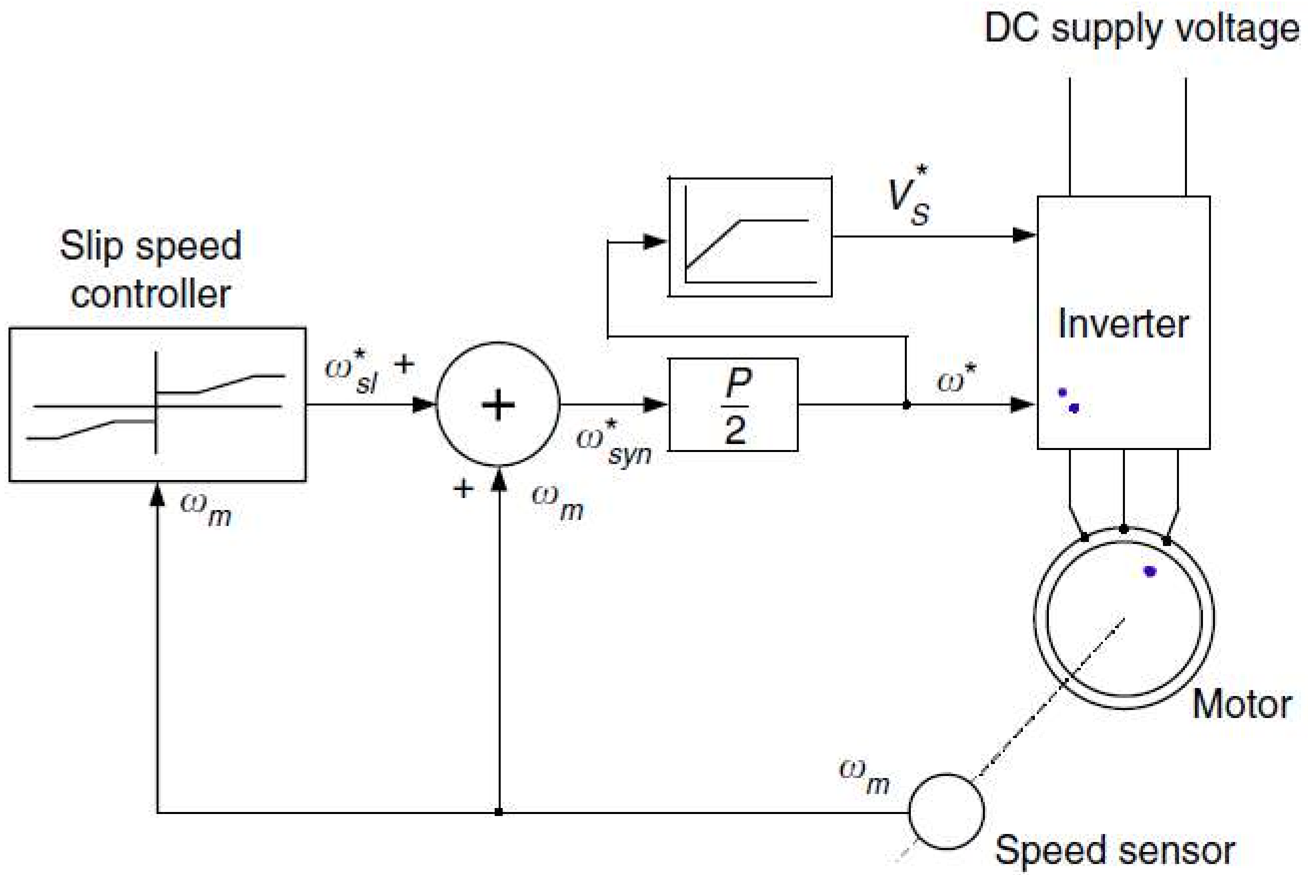
Motor

E.F

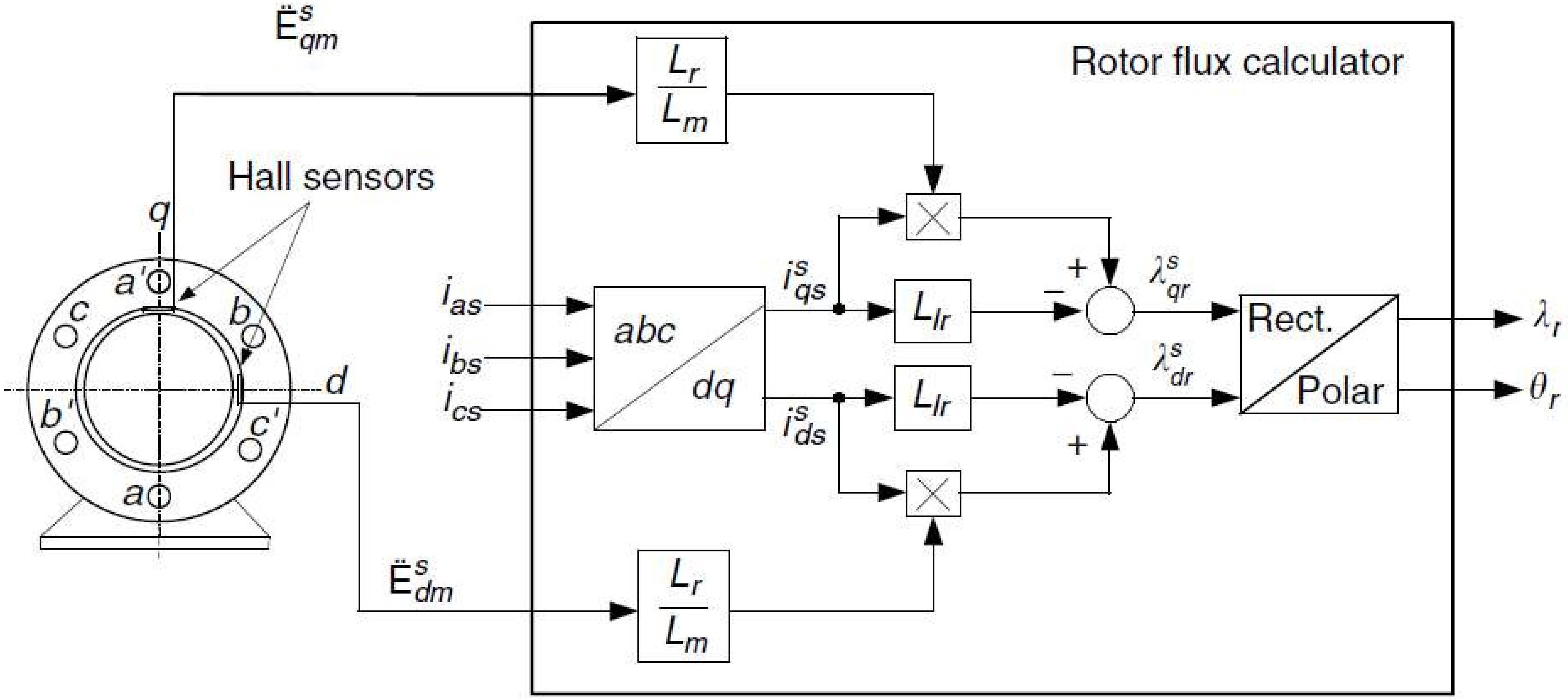
Regen.
Gen.

$E > V$ $\quad -I_a$

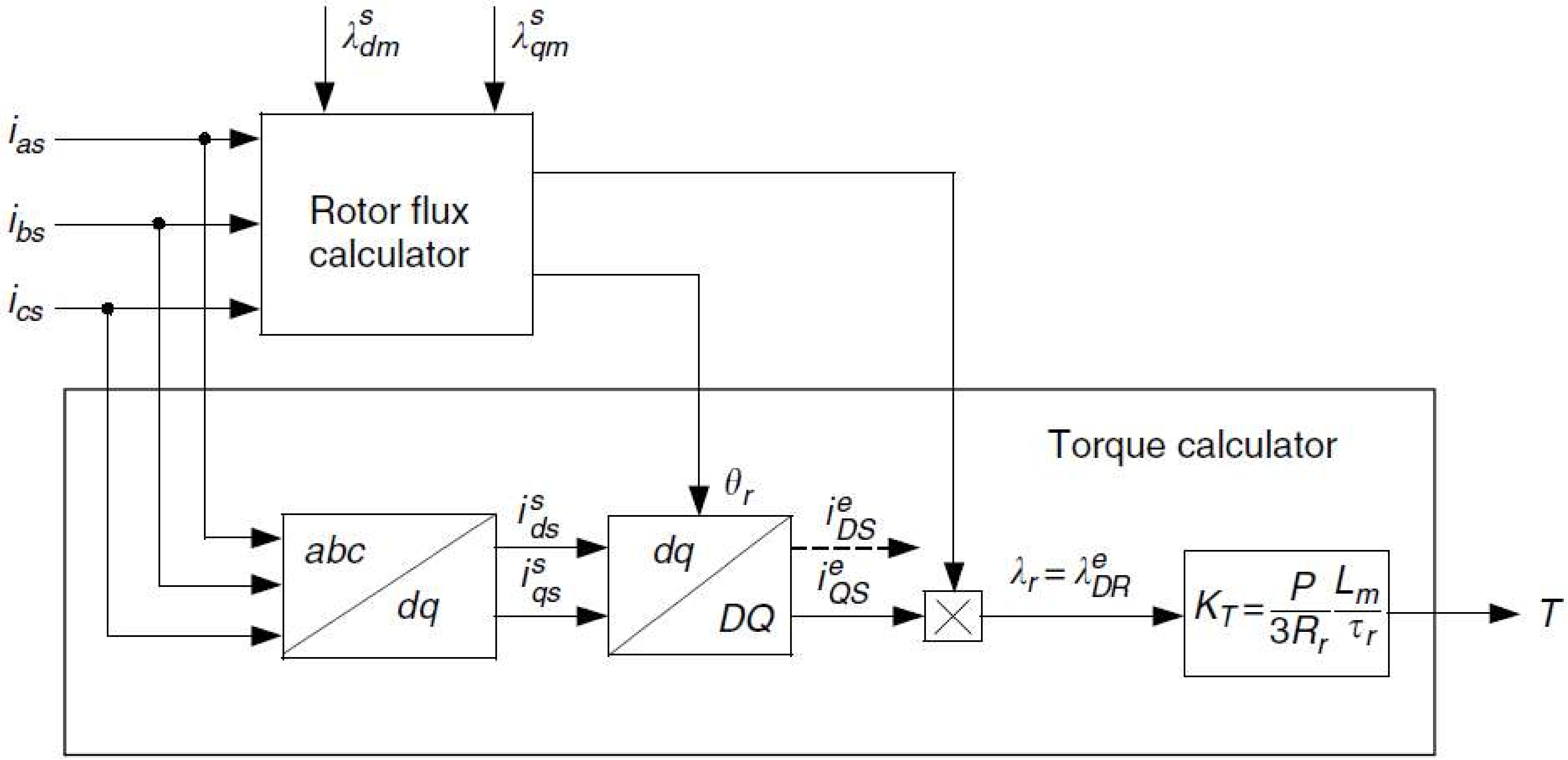
General Configuration of Constant v/f control



Determination of the magnitude and position of the rotor flux vector using Hall sensor and a rotor flux calculator



Torque Calculator



Vector control system for an induction motor with direct rotor flux orientation