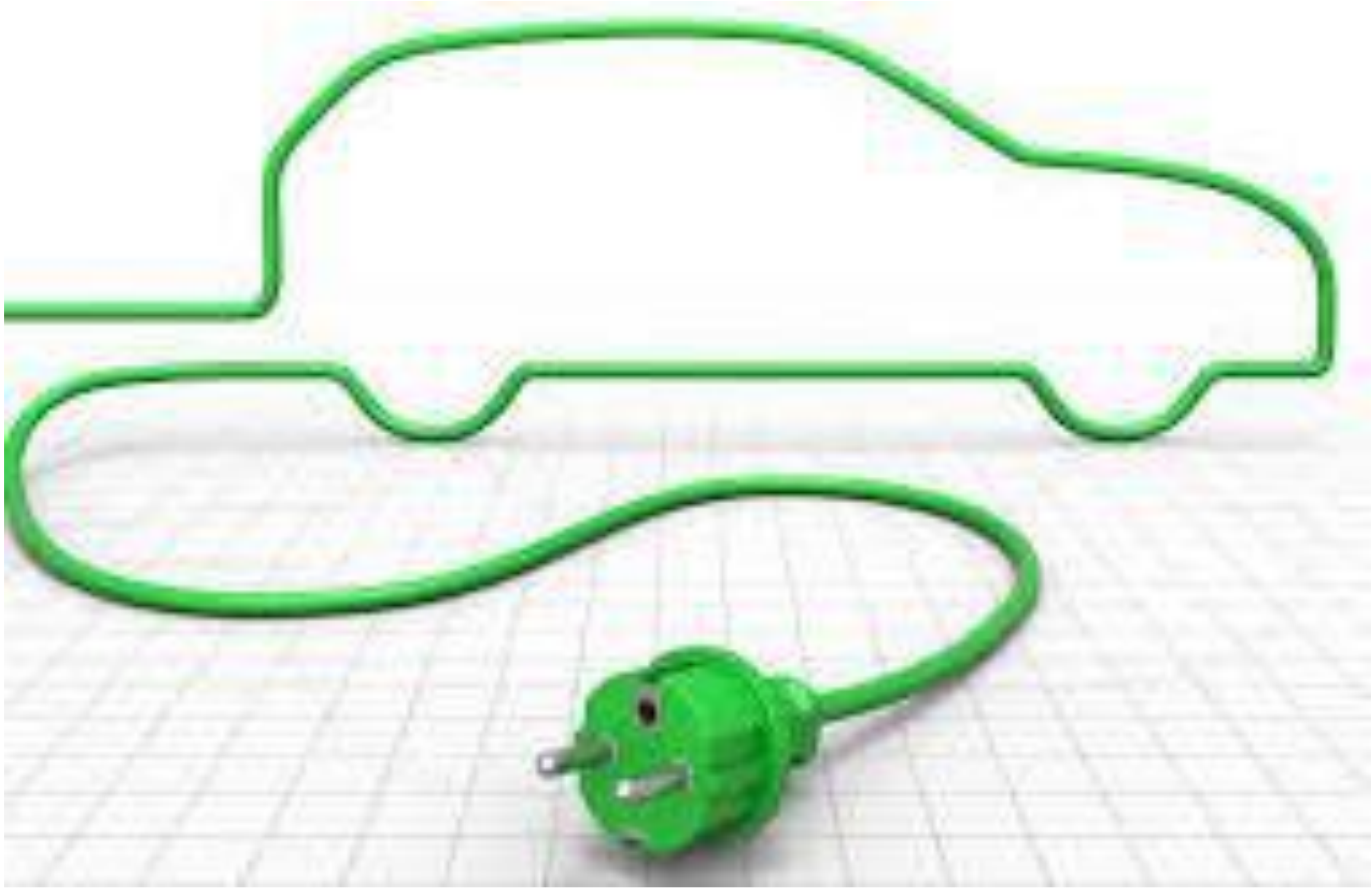
EE469: Electric & Hybrid Vehicles



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Course code	Course Name	L-T-P -Credits	Year of Introduction
EE469	Electric and Hybrid Vehicles	3-0-0-3	2016

Prerequisite : Nil

Course Objectives

- To present a comprehensive overview of Electric and Hybrid Electric Vehicles

Syllabus

Introduction to Hybrid Electric Vehicles, Conventional Vehicles, Hybrid Electric Drive-trains, Electric Propulsion unit, Configuration and control of DC Motor drives, Induction Motor drives, Permanent Magnet Motor drives, switched reluctance motor, Energy Storage Requirements in Hybrid and Electric Vehicles, Sizing the drive system, Design of a Hybrid Electric Vehicle , Energy Management Strategies.

Expected outcome.

The students will be able to

i. Choose a suitable drive scheme for developing an electric hybrid vehicle depending on resources
ii. Design and develop basic schemes of electric vehicles and hybrid electric vehicles.
iii. Choose proper energy storage systems for vehicle applications
iv. Identify various communication protocols and technologies used in vehicle networks.

Text Book:

1. Iqbal Hussein, Electric and Hybrid Vehicles: Design Fundamentals, CRC Press, 2003

References:

1. James Larminie, John Lowry, Electric Vehicle Technology Explained, Wiley, 2003.
2. Mehrdad Ehsani, YimiGao, Sebastian E. Gay, Ali Emadi, Modern Electric, Hybrid Electric and Fuel Cell Vehicles: Fundamentals, Theory and Design, CRC Press, 2004.

Course Plan

Module	Contents	Hours	Sem. Exam Marks
I	Introduction to Hybrid Electric Vehicles: History of hybrid and electric vehicles, social and environmental importance of hybrid and electric vehicles, impact of modern drive-trains on energy supplies. Conventional Vehicles: Basics of vehicle performance, vehicle power source characterization, transmission characteristics, mathematical models to describe vehicle performance.	7	15%
II	Hybrid Electric Drive-trains: Basic concept of hybrid traction, introduction to various hybrid drive-train topologies, power flow control in hybrid drive-train topologies, fuel efficiency analysis. Electric Drive-trains: Basic concept of electric traction, introduction to various electric drive-train topologies, power flow control in electric drive-train topologies, fuel efficiency analysis.	7	15%
FIRST INTERNAL EXAMINATION			
III	Electric Propulsion unit: Introduction to electric components used in hybrid and electric vehicles, Configuration and control of DC Motor drives, Configuration and control of Induction Motor drives	7	15%
IV	Energy Storage: Introduction to Energy Storage Requirements in Hybrid and Electric Vehicles, Battery based energy storage and its analysis, Fuel Cell based energy storage and its analysis, Hybridization of different energy storage devices.	7	15%
SECOND INTERNAL EXAMINATION			
V	Sizing the drive system: Matching the electric machine and the internal combustion engine (ICE), Sizing the propulsion motor, sizing the power	7	20%

V	Sizing the drive system: Matching the electric machine and the internal combustion engine (ICE), Sizing the propulsion motor, sizing the power electronics, selecting the energy storage technology,	**7**	20%
VI	Communications, supporting subsystems: In vehicle networks- CAN, Energy Management Strategies: Introduction to energy management strategies used in hybrid and electric vehicles, classification of different energy management strategies, comparison of different energy management strategies	**7**	20%
END SEMESTER EXAM			

QUESTION PAPER PATTERN:

Maximum Marks: 100 Exam Duration: 3Hourrs.

Part A: 8 compulsory questions.

One question from each module of Modules I - IV; and two each from Module V & VI.

Student has to answer all questions. (8 x5)=40

Part B: 3 questions uniformly covering Modules I & II. Student has to answer any 2 from the 3 questions: (2 x 10) =20. Each question can have maximum of 4 sub questions (a,b,c,d), if needed.

Part C: 3 questions uniformly covering Modules III & IV. Student has to answer any 2 from the 3 questions: (2 x 10) =20. Each question can have maximum of 4 sub questions (a,b,c,d), if needed.

Module 1: Introduction -

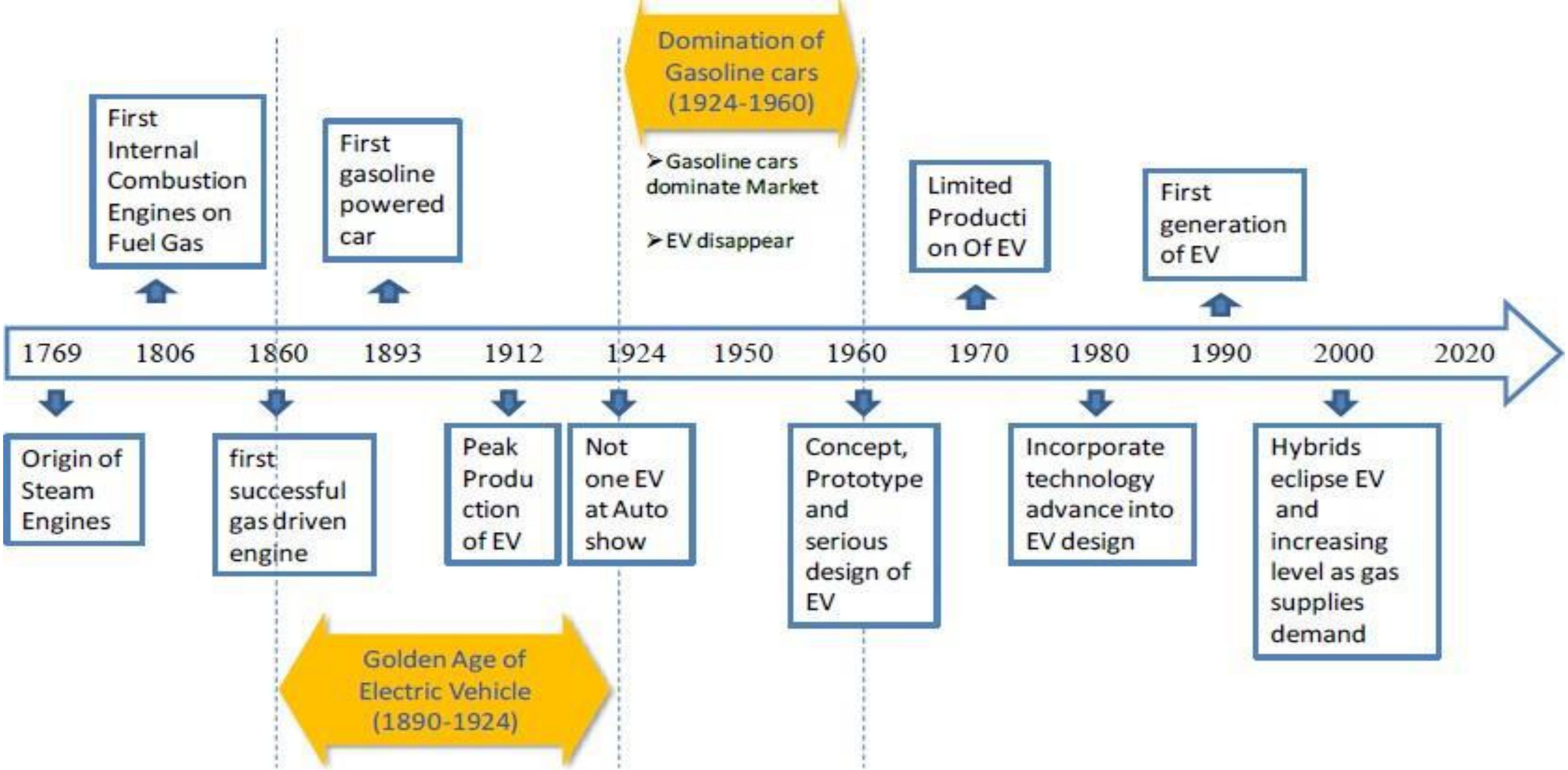
- What is a hybrid?
- A hybrid vehicle combines any two power (energy) sources.
- Possible combinations include diesel/electric, gasoline/fly wheel, and fuel cell (FC)/battery.
- One energy source is storage, and the other is conversion of a fuel to energy.
- **Hybrid electric vehicle (HEV)** Consistent with the definition of hybrid above, the hybrid electric vehicle combines a gasoline engine with an electric motor.

FIRST ELECTRIC CAR

In the early 1900s, electric vehicle was reserved for dignitaries likes Thomas Edison, John D. Rockefeller, Jr. and Clara Ford, the wife of Henry Ford due to its quiet ride over the vibrating and polluting I.C. engine.

Source : BU-1003: Electric vehicle, Battery University

Historical Development of EV



Domination of Gasoline cars (1924-1960)

- Gasoline cars dominate Market
- EV disappear

First Internal Combustion Engines on Fuel Gas

First gasoline powered car

Limited Producti on Of EV

First generation of EV

Origin of Steam Engines

first successful gas driven engine

Peak Produ ction of EV

Not one EV at Auto show

Concept, Prototype and serious design of EV

Incorporate technology advance into EV design

Hybrids eclipse EV and increasing level as gas supplies demand

Golden Age of Electric Vehicle (1890-1924)

Historical Development of EV

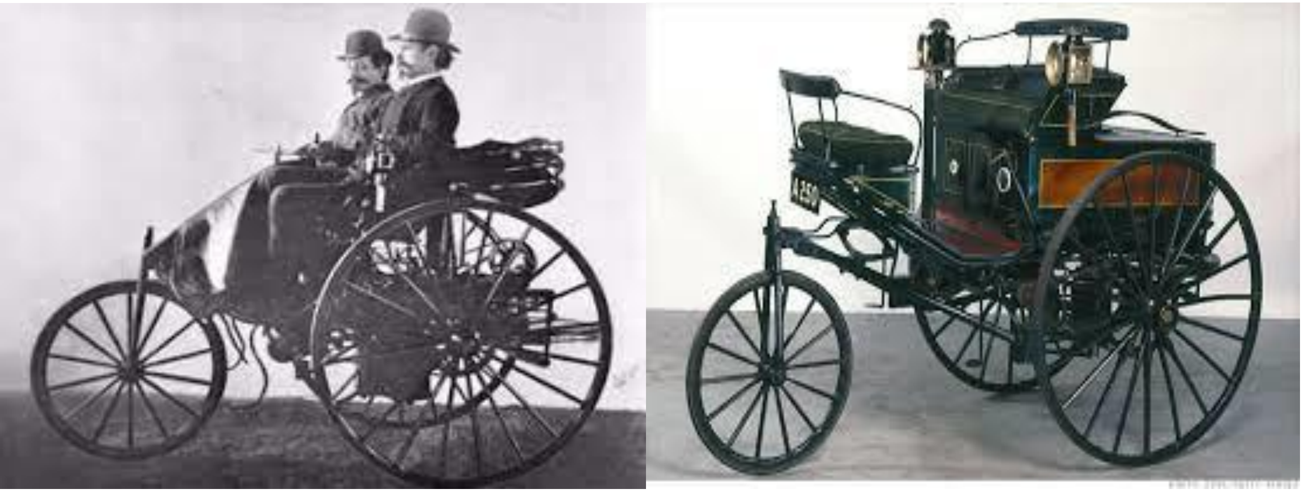
1769

- *1st Steam Powered Vehicle*
- *Nicolas Joseph Cugnot & M. Brezin*
- *Speed upto 6km/hr*
- *Heavy*
- *Poor fuel economy*
- *Feed water was a necessary input*

Historical Development of EV

- **1807**
- *1st Internal Combustion Engine*
- *Francois Issac de Rivaz*
- *Using a mixture of Hydrogen & Oxygen to generate energy*

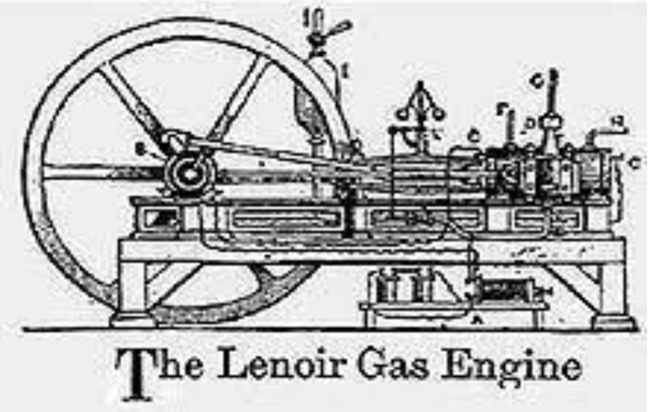
- **1825**
- *Steam Car- successfully completed 85mile in 10hrs.*
- *Goldsworthy Gurney*



Historical Development of EV

- **1839-** Robert Anderson
- *First Electric vehicle*

- **1860-** *First Sucessful 2 Stroke gas driven engine*
- Jean Joseph Etienne Lenoir



- **1886-** *Electric powered taxicab*
- ***<u>1890-1910: Invention of Hybrid Vehicle</u>***

Historical Development of EV

- ***Electrical vehicle*** marked from 1890 to 1924 with peak production of electric vehicles in 1912
- ***Gasoline car*** was far superior to that of either a steam or an electric car and dominated the automobile market from 1924 to 1960.
- Engineers recognized that the good features of the gasoline engine could be combined with those of the electric motor to produce a superior car.
- A marriage of the two yields the hybrid automobile.

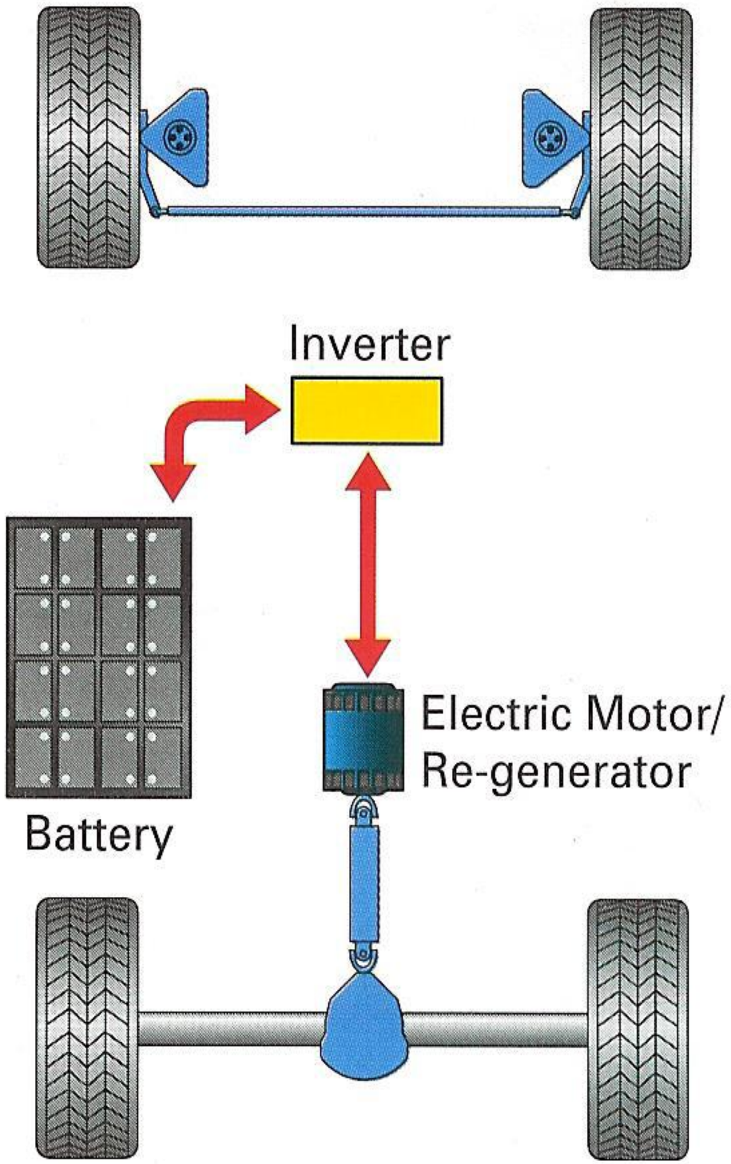
Historical Development of EV

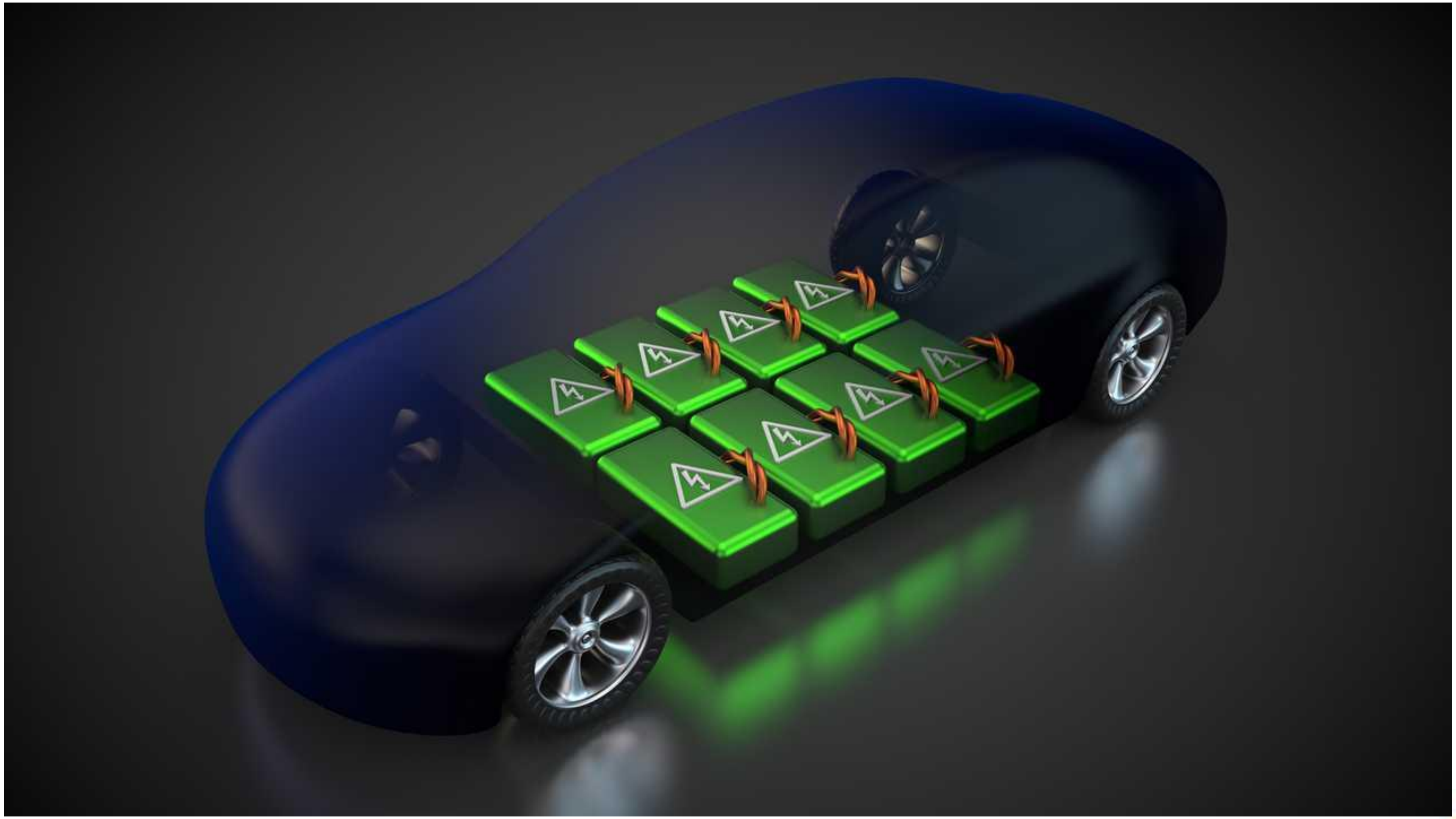
- To save money
- To reduce negative impacts on environment
- 1997- Audi Duo: 1st European hybrid car into mass production
- 2000- Toyota Prius & Honda Insight-1st Mainstream HEVs


TESLA

ELECTRIC VEHICLE COMPONENTS

- **Motor**
- **Battery**
- **Transmission**
- **Motor controller**
- **Vehicle controller**

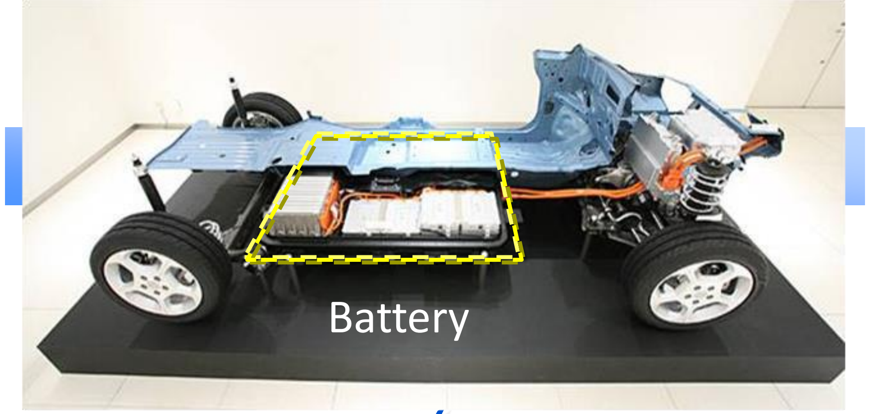




BATTERY FUNDAMENTALS

NISSAN LEAF VEHICLE STRUCTURE

Chassis



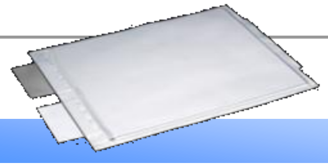
B

Battery Management System
Junction Box
Service Disconnect Switch Etc

Module

48 modules / vehicle

Cell



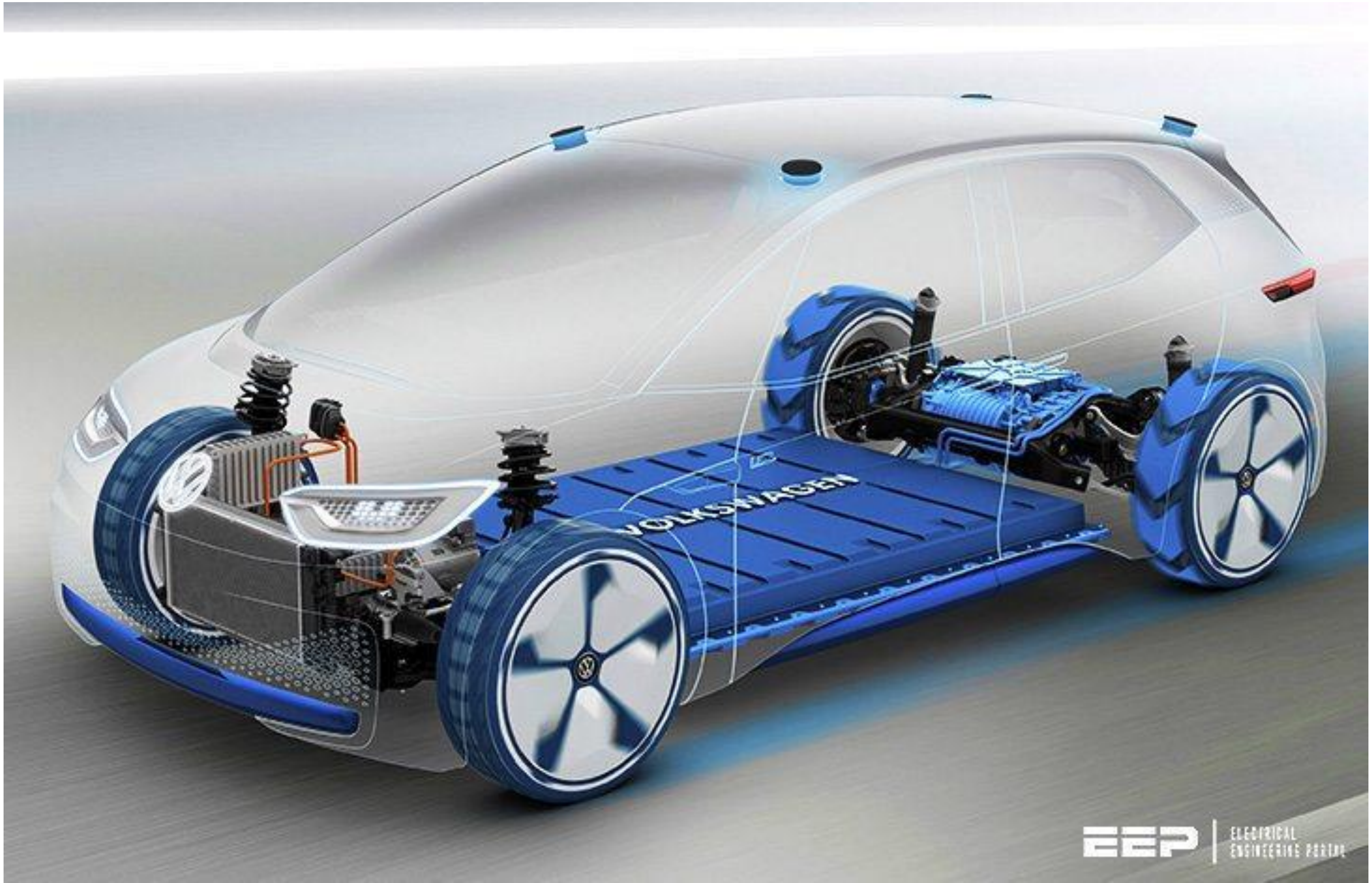
192 cells / vehicle
4 cells / module

Source : Nissan

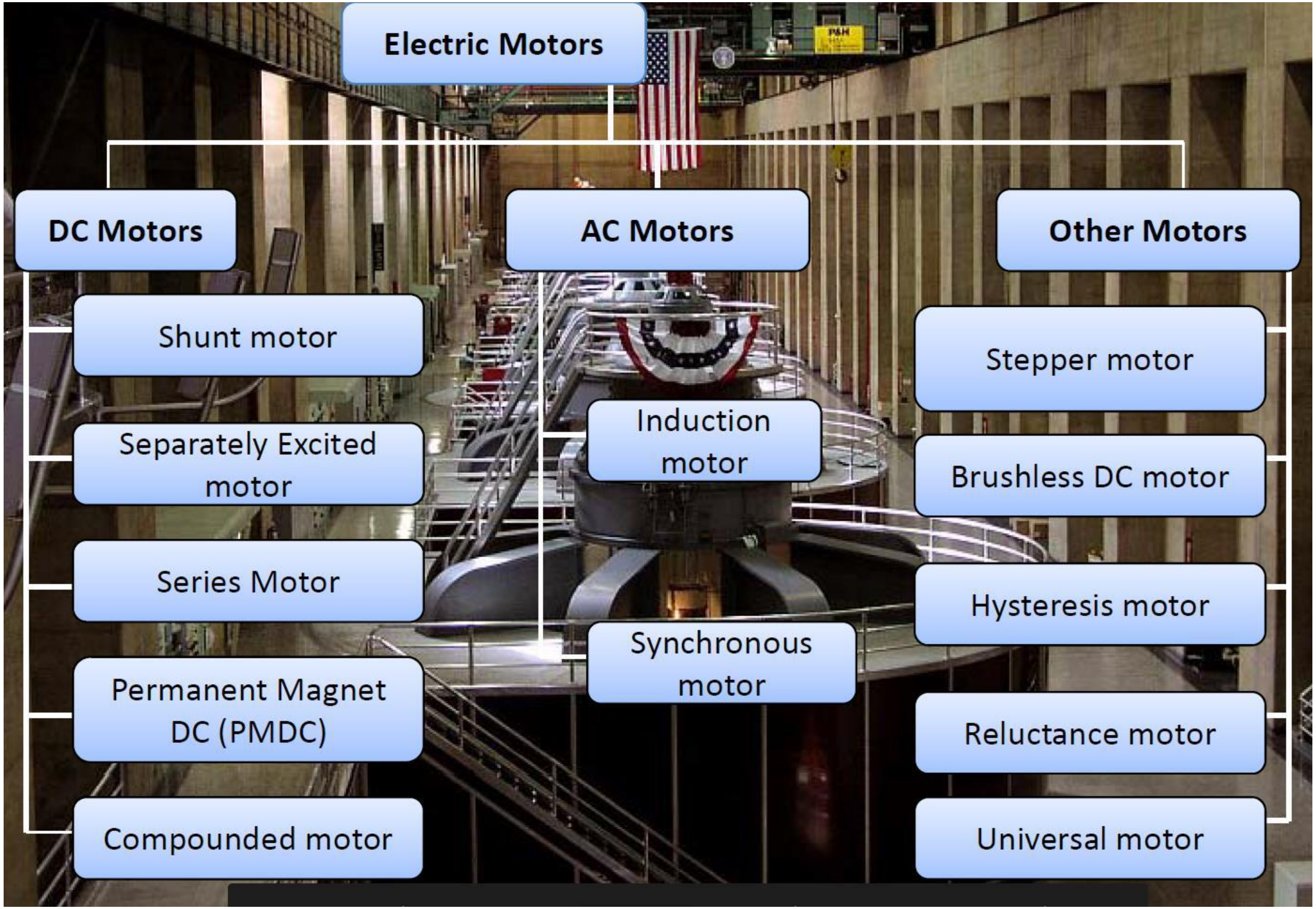
BATTERY PACK OF CHEVY BOLT

Source : Battery University

BATTERY PACK ON VOLKSWAGON



TYPES OF MOTORS



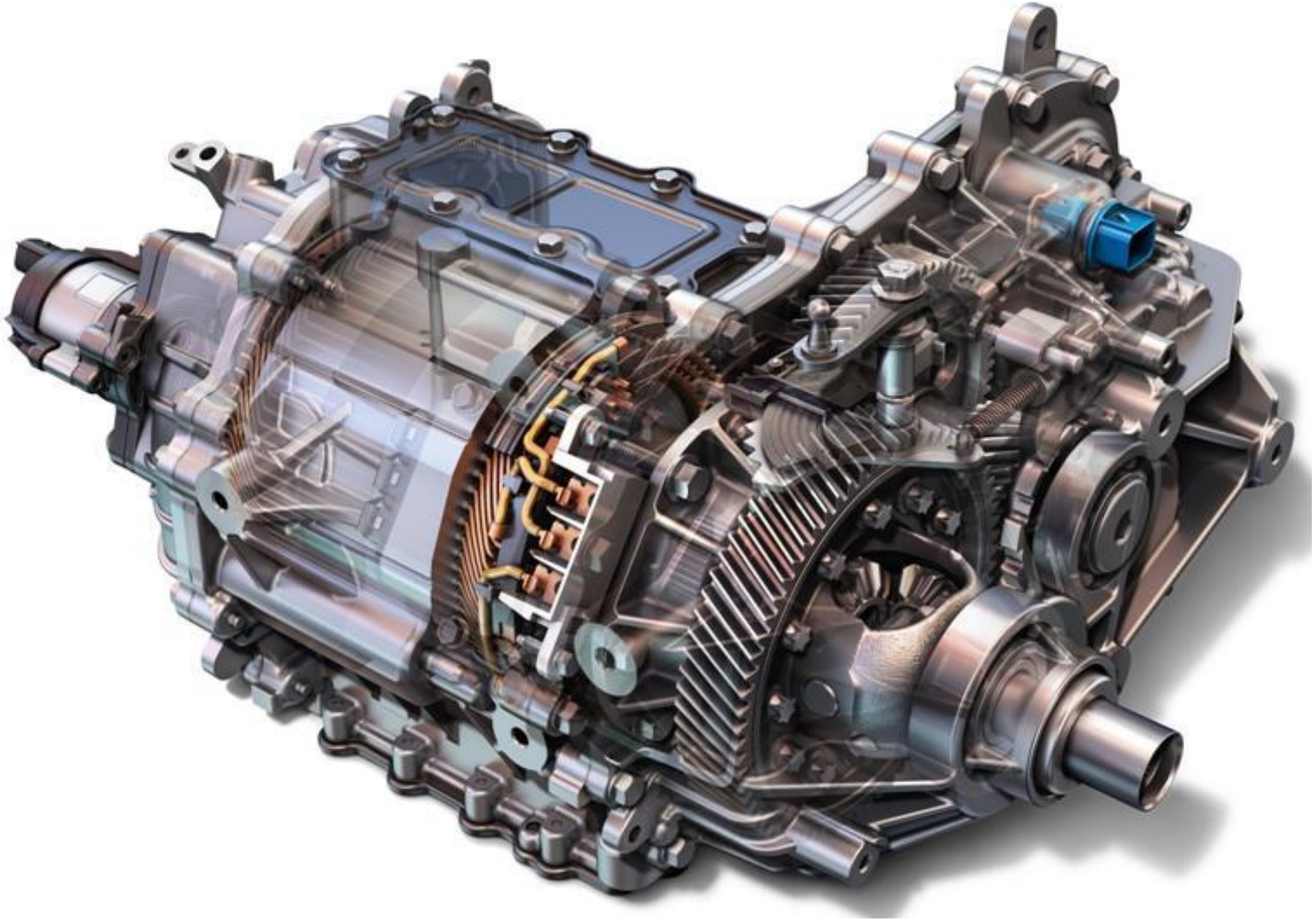
Electric Motors

DC Motors
- Shunt motor
- Separately Excited motor
- Series Motor
- Permanent Magnet DC (PMDC)
- Compounded motor

AC Motors
- Induction motor
- Synchronous motor

Other Motors
- Stepper motor
- Brushless DC motor
- Hysteresis motor
- Reluctance motor
- Universal motor

ELECTRIC MOTOR USED IN ELECTRIC VEHICLES



AIR POLLUTION FROM COAL-BURNING INDUSTRIAL PLANT IN INDIA

GREEN VEHICLE TECHNOLOGIES

1905-2020

- Spark Ignition Engines
- Compression Ignition Engines

2021-2030

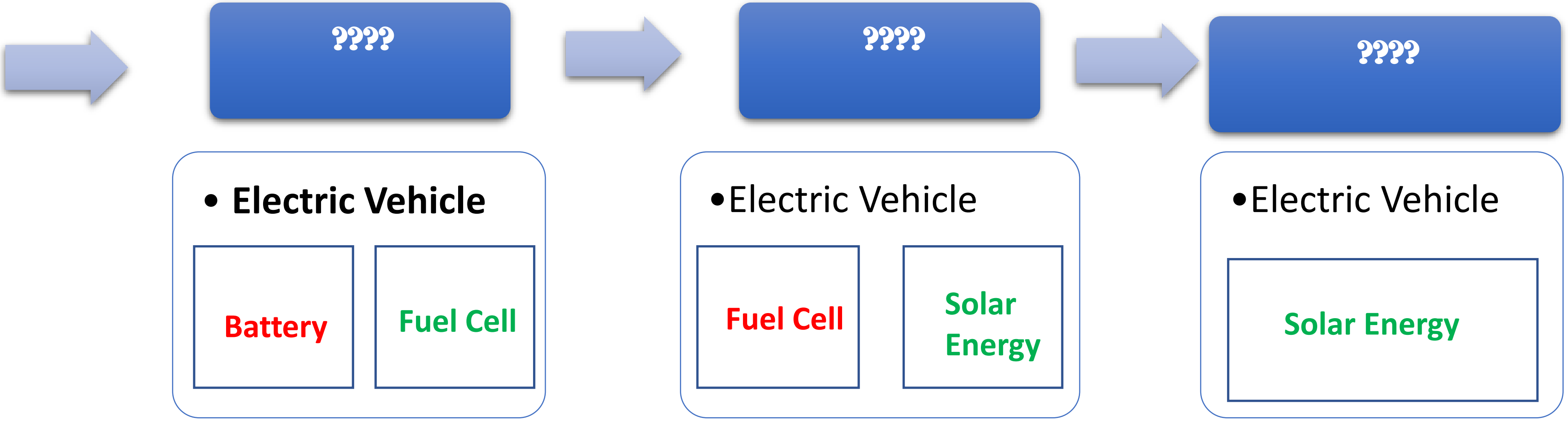
- HCCI (Homogeneous Charge Compression Ignition)
- RCCI (Reactivity Controlled Compression Ignition)

2030- ????

- Hybrid Electric Vehicle

Electric Motor	HCCI Engine

GREEN VEHICLE TECHNOLOGIES



????

- **Electric Vehicle**

Battery

Fuel Cell

????

- Electric Vehicle

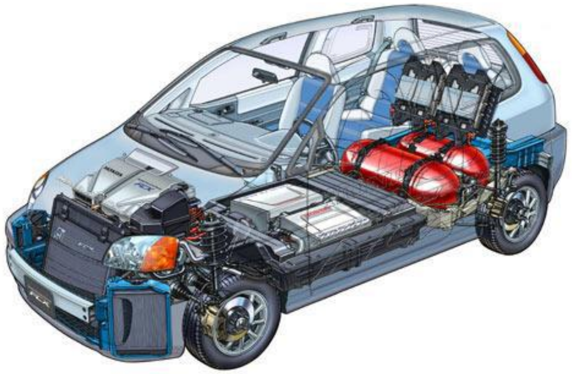
Fuel Cell

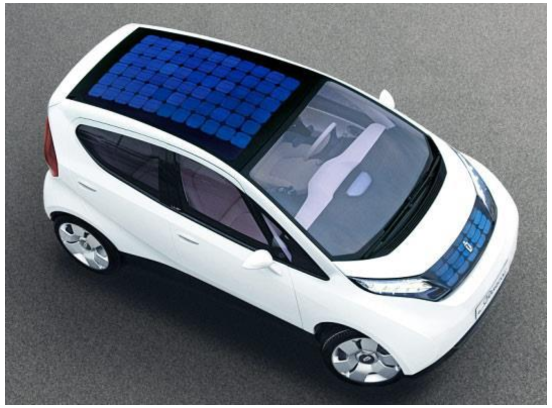
Solar Energy

????

- Electric Vehicle

Solar Energy





In Future cars won’t be called as

CARS

but ???

COWS

COMPUTERS ON WHEELS

ACKNOWLEDGEMENTS

Thanks are due to the Inventors of

Robert E Kahn

Internet

Vint Cerf

Larry Page

Google

Sergey Brin

Larry Tesler

Copy & Paste

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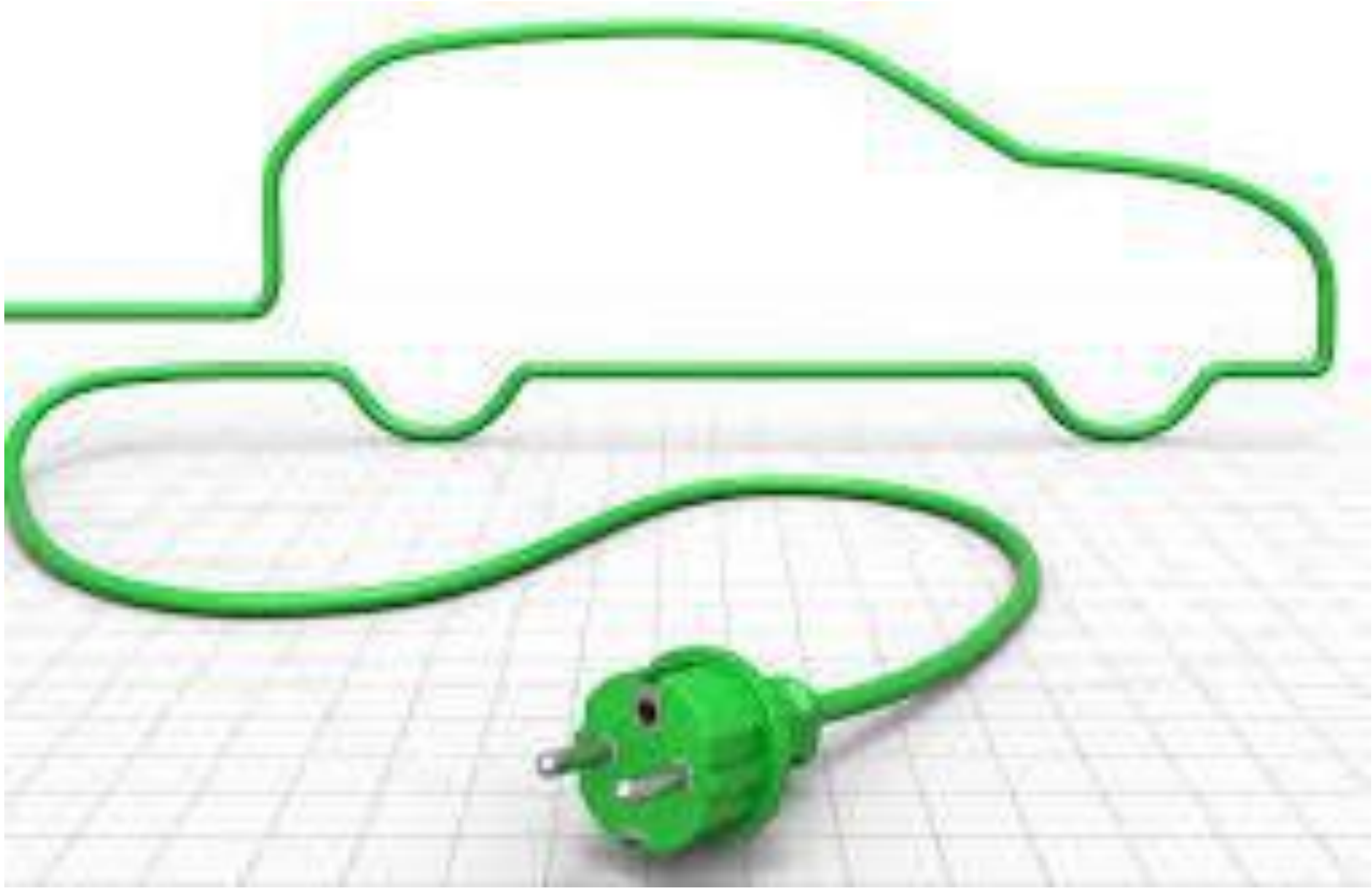

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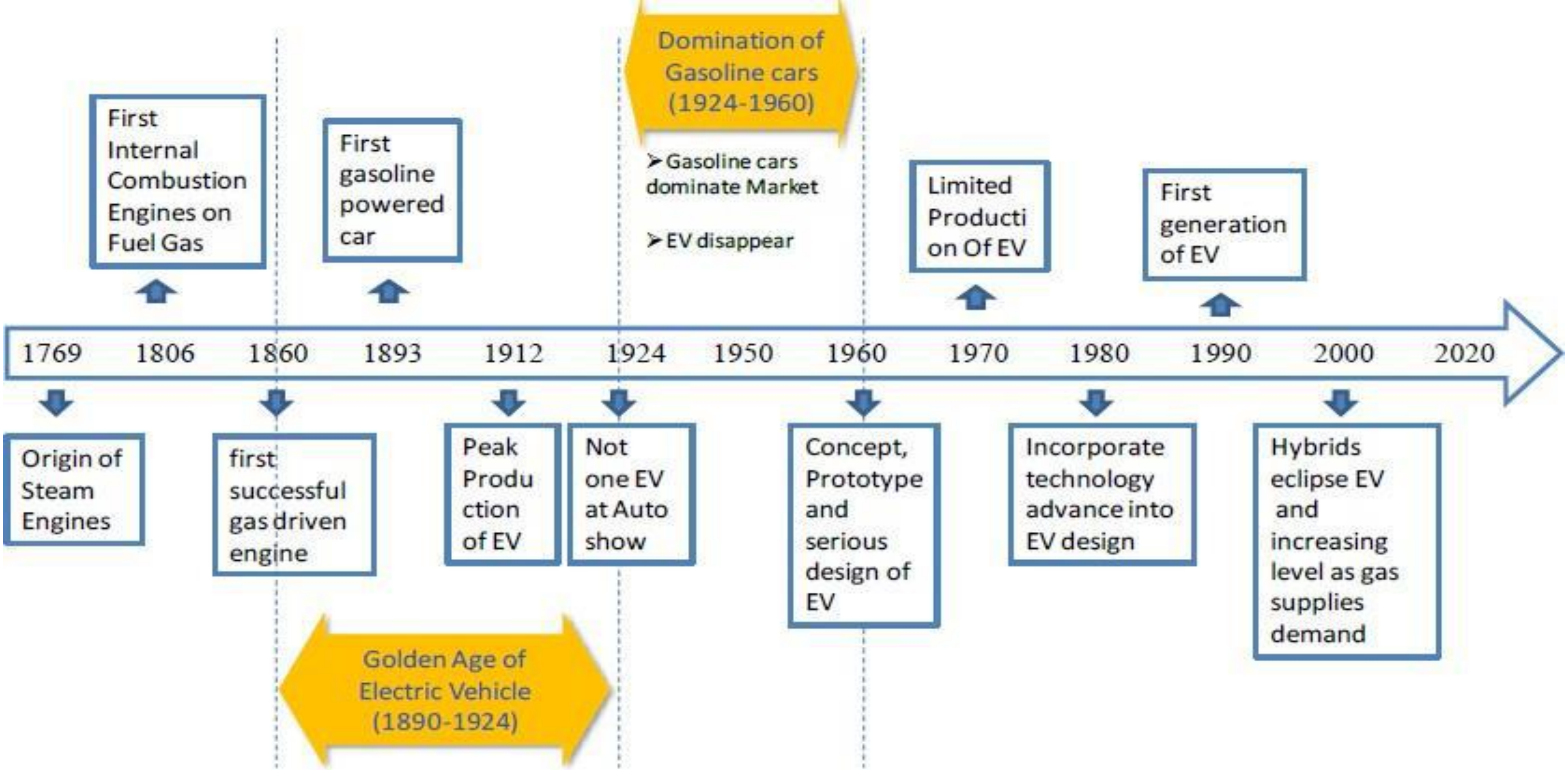

1769 1806 1860 1893 1912 1924 1950 1960 1970 1980 1990 2000 2020

Origin of Steam Engines

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first successful gas driven engine

First gasoline powered car

Golden Age of Electric Vehicle (1890-1924)

Peak Production of EV

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Concept, Prototype and serious design of EV

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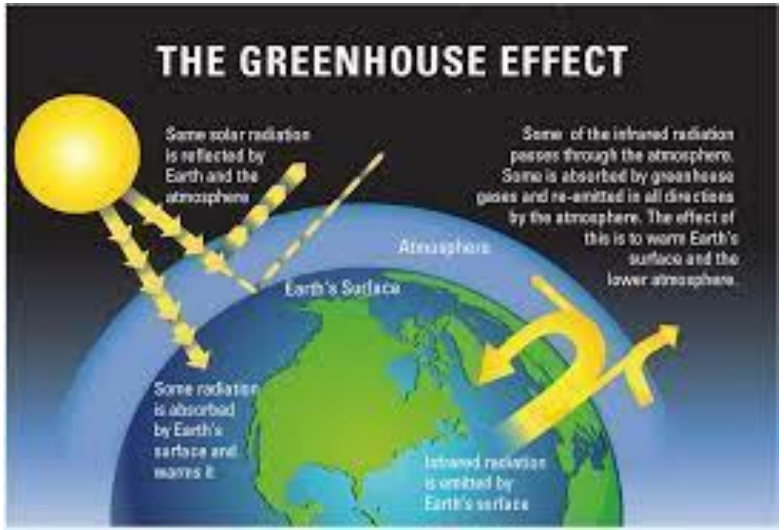
Incorporate technology advance into EV design

First generation of EV

Hybrids eclipse EV and increasing level as gas supplies demand

Social and Environmental Importance of Hybrid & Electric Vehicle

- Growing presence of global warming and irreversible climate change draws increasing amounts of concern from the world's population.
- Cars & Trucks are responsible for almost 25% of CO2 emission.
- Need of *high efficiency, clean, and safe transportation.*
- Electric vehicles, hybrid electric vehicles, and fuel cell vehicles have been typically proposed to replace conventional vehicles in the near future.
- ***Air pollution, gas emissions causing global warming, and petroleum resource depletion*** due to the use of conventional engines gave birth to the development of electric vehicles.



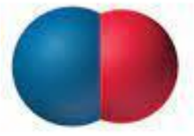
AIR POLLUTION FROM COAL-BURNING INDUSTRIAL PLANT IN INDIA

A) Air Pollution

- Combustion is a reaction between the fuel and the air that releases heat and combustion products. The heat is converted to mechanical power by an engine and the combustion products are released into the atmosphere.
- Combustion products contain CO2, water, certain amount of nitrogen oxides (NO*x*), carbon monoxides (CO), and unburned hydrocarbons (HC), all of which are toxic to human health.

Nitrogen Oxides

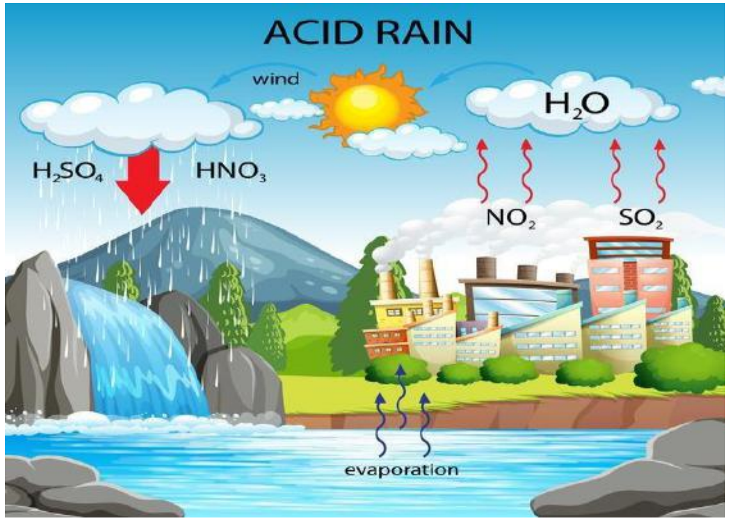
- .Nitrogen oxides (NOx) result from the reaction between nitrogen in the air and oxygen.
- The most commonly found nitrogen oxide is nitric oxide (NO) nitrogen dioxide (NO2) and traces of nitrous oxide (N2O) are also present.
- Nitrogen dioxide is partly responsible for smog; its brownish color makes smog visible.
- Nitrogen dioxide reacts with atmospheric water to form nitric acid (HNO3), which dilutes in rain.
- This phenomenon is referred to as "*acid rain*" and is responsible for the destruction of forests in industrialized countries. Acid rain also contributes to the degradation of historical monuments made of marble.



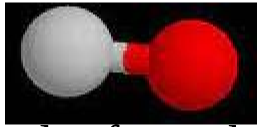
NO

N_2O

NO_2



Carbon Monoxide



- Carbon monoxide results from the incomplete combustion of hydrocarbons due to a lack of oxygen. It is a poison to human and animal beings that breathe it.
- Once carbon monoxide reaches the blood cells, it fixes to the hemoglobin in place of oxygen, thus diminishing the quantity of oxygen that reaches the organs.
- Dizziness is the first symptom of carbon monoxide poisoning, which can rapidly lead to death.

Unburned Hydrocarbons

- Unburned hydrocarbons are a result of the incomplete combustion of hydrocarbons. Depending on their nature, unburned hydrocarbons may be harmful to living beings.
- Unburned hydrocarbons are also responsible for smog: the Sun’s ultraviolet radiations interact with unburned hydrocarbons and NO in the atmosphere to form ozone and other products.
- It is colorless but very dangerous, and poisons as it attacks the membranes of living cells, thus causing them to age prematurely or to die.

Other Pollutants

- Impurities in fuels result in the emission of pollutants. The major impurity is sulfur, which is mostly found in diesel and jet fuel and also in gasoline and natural gas.
- The combustion of sulfur (or sulfur compounds such as hydrogen sulfide) with oxygen releases sulfur oxides (SO_x). Sulfur dioxide (SO2) is the major product of this combustion. Sulfuric acid, a major component of acid rain.

B) Global Warming

- Global warming is a result of the “greenhouse effect” induced by the presence of carbon dioxide and other gases.
- These gases trap the Sun’s infrared radiation reflected by the ground, thus retaining the energy in the atmosphere and increasing the temperature.
- An increased Earth temperature results in major ecological damages to its ecosystems .
- The melting of the polar icecaps, another major result of global warming, raises the sea level and can cause the permanent inundation of coastal regions, and sometimes of entire countries.
- Transportation accounts for a large share (32% from 1980 to 1999) of carbon dioxide emissions

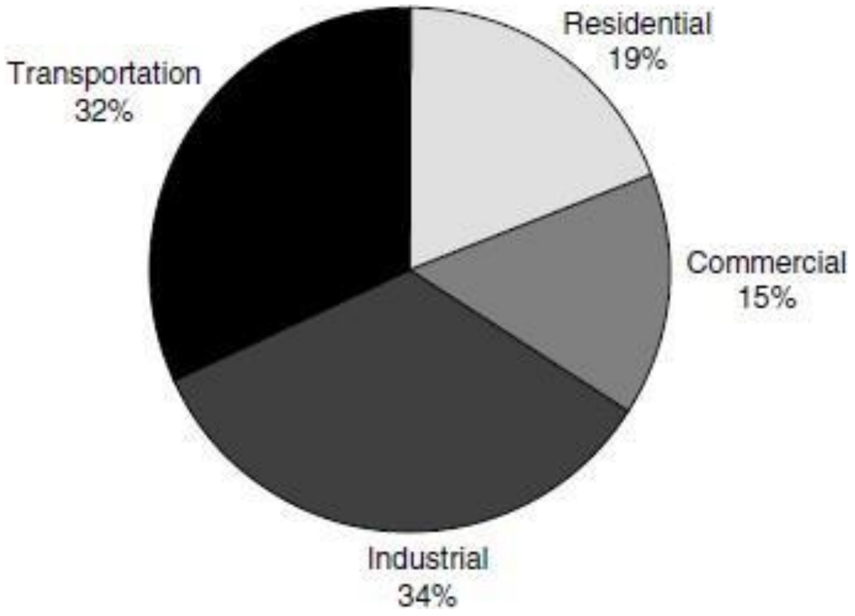


Fig 1: Carbon dioxide emission distribution from 1980 to 1999

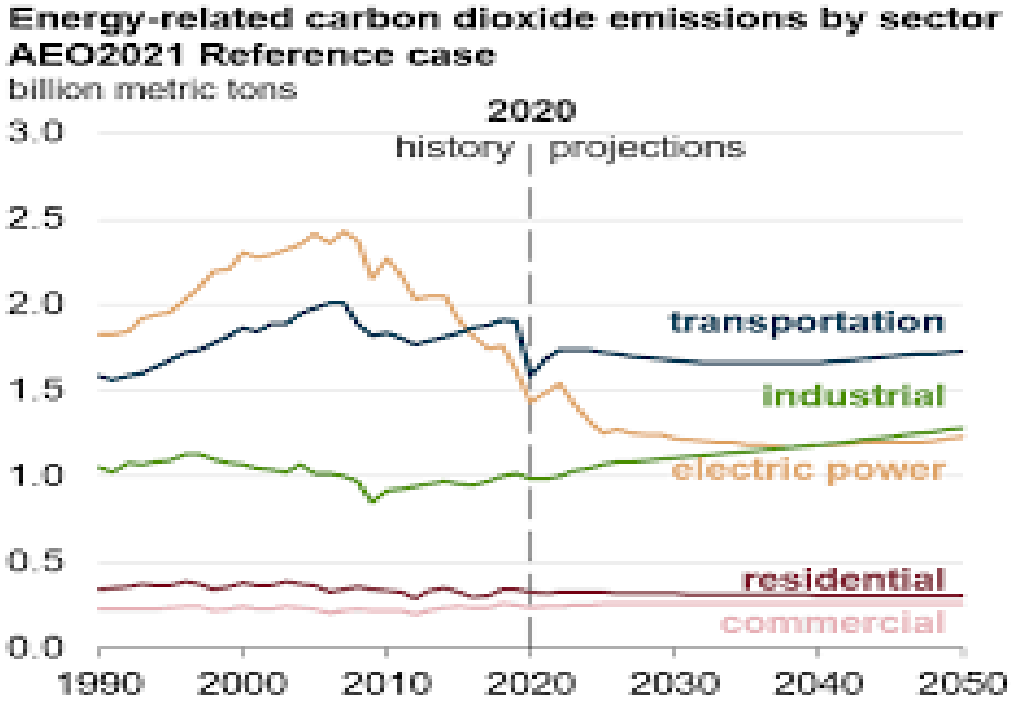
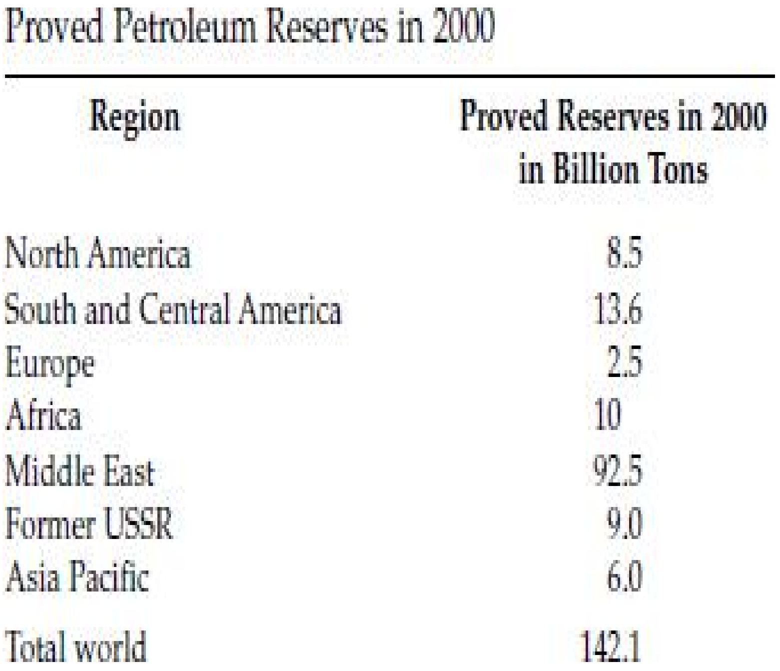


Fig 2: Trend in carbon dioxide emissions

- Figure 2 - transportation sector is clearly now the major contributor of carbon dioxide emissions.

C) Depletion of Petroleum Resources

- The vast majority of fuels used for transportation are liquid fuels originating from petroleum.
- Petroleum is a fossil fuel, resulting from the decomposition of living matters that were imprisoned millions of years ago (Ordovician, 600 to 400 million years ago) in geologically stable layers.
- The process is roughly the following: living matters (mostly plants) die and are slowly covered by sediments. Over time, these accumulating sediments form thick layers, and transform to rock.
- The living matters are trapped in a closed space, where they encounter high pressures and temperatures, and slowly transform into either hydrocarbons or coal, depending on their nature.
- This process took millions of years to accomplish. This is what makes the Earth's resources in fossil fuels finite.



Proved Petroleum Reserves in 2000

Region	Proved Reserves in 2000 in Billion Tons
North America	8.5
South and Central America	13.6
Europe	2.5
Africa	10
Middle East	92.5
Former USSR	9.0
Asia Pacific	6.0
Total world	142.1

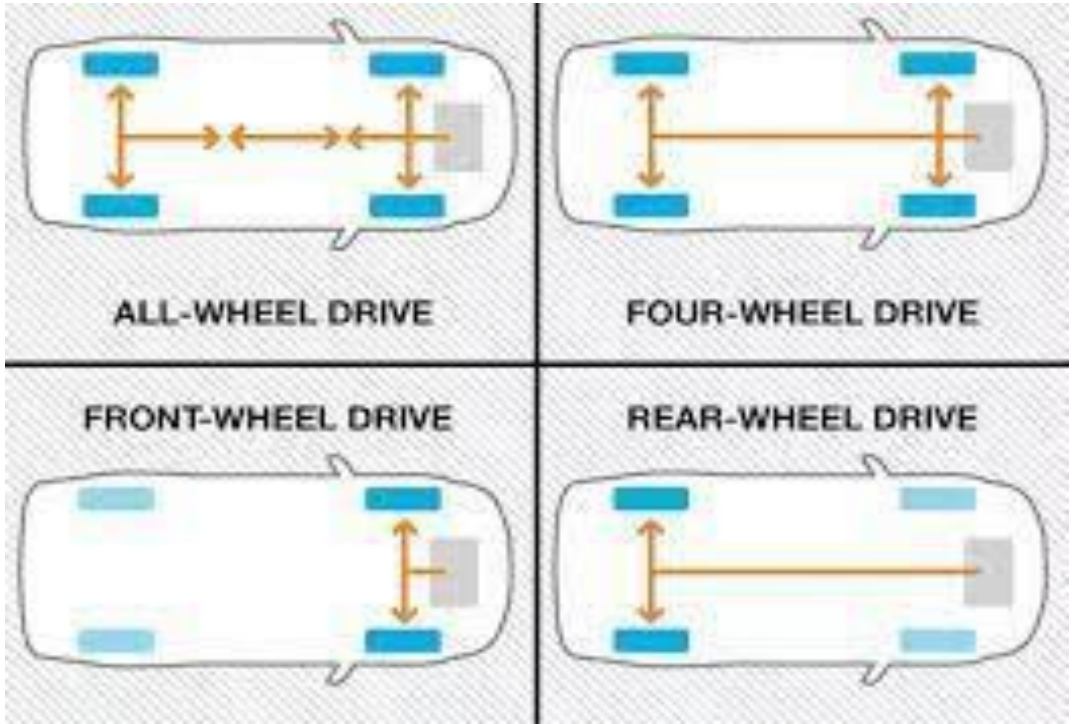
- The disadvantages of conventional vehicles shows the social and environmental importance of EV and HEV

Advantages of Hybrid Vehicles

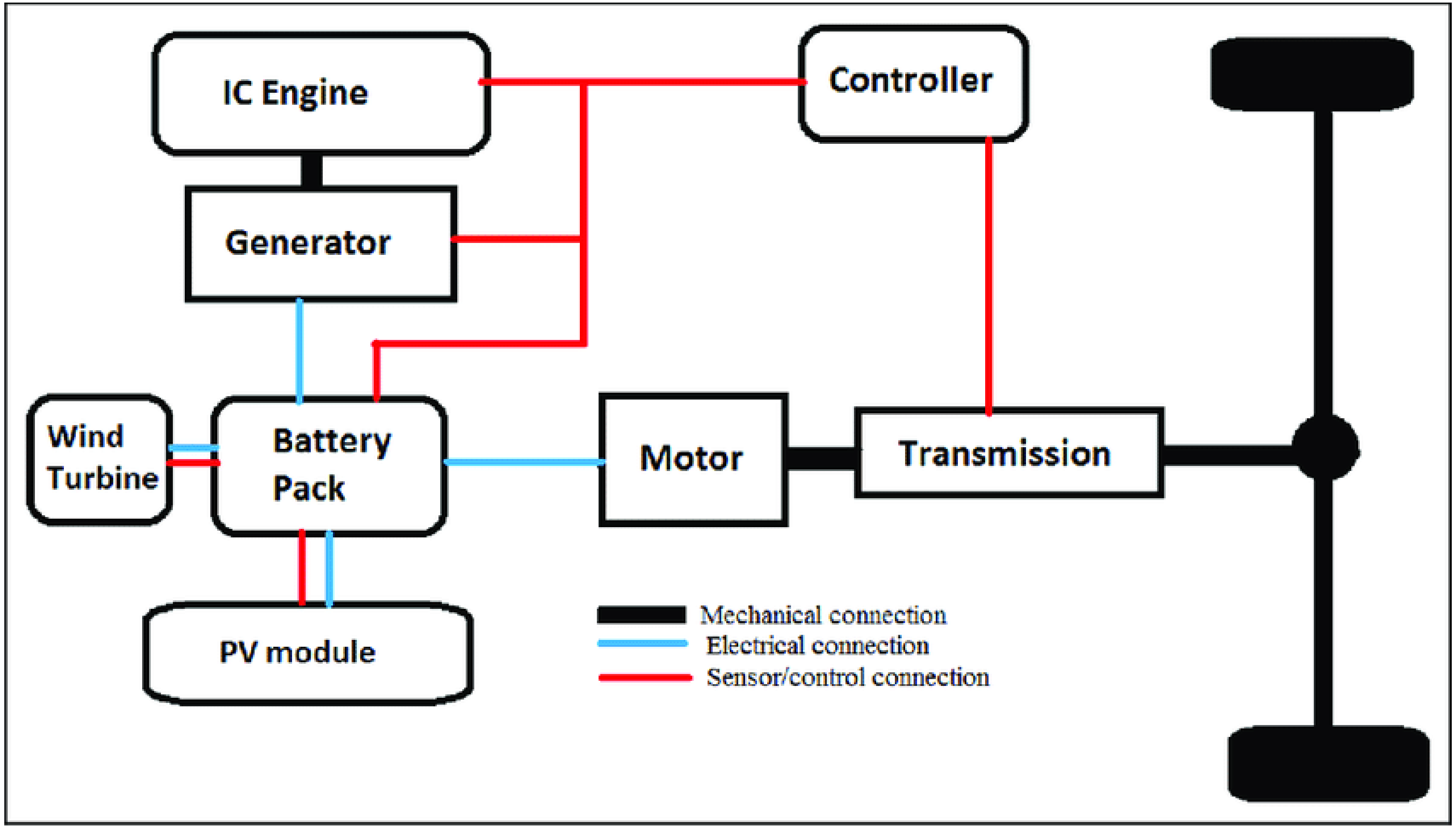
- The electric motor is far more efficient (70%-85% efficiency) than the heat engine.
- EV’s can use regenerative braking (regain 30% of energy used, theoretically).
- HEV’s are more environmentally friendly (if electricity if produced from renewable sources)
- Reduction in engine and vehicle weight
- Fuel efficiency is increased
- Emissions are decreased
- Cut emissions of global warming pollutants by 1/3 or 1/2
- Reduce the dependency on fossil fuels
- ~2 times more efficient than conventional engines

Impact of Modern Drivetrains

- Drivetrain - group of components that deliver power to the driving wheels.
- Drivetrain is a series of parts that work together to transfer the rotational power produced in engine to wheels so car can move.
- To couple the engine that produces the power to the driving wheels that use this mechanical power to rotate the axle.
- The operating speed of the engine and wheels are also different and must be matched by the correct gear ratio.
- As the vehicle speed changes, the ideal engine speed must remain approximately constant for efficient operation and so this gearbox ratio must also be changed, either manually, automatically or by an automatic continuous variation.
- There are mainly 4 different types of drivetrain used in vehicles
  - ❖ Rear-wheel drive (RWD)
  - ❖ Front-wheel drive (FWD)
  - ❖ All-wheel drive (AWD)
  - ❖ Four-wheel drive (4WD)

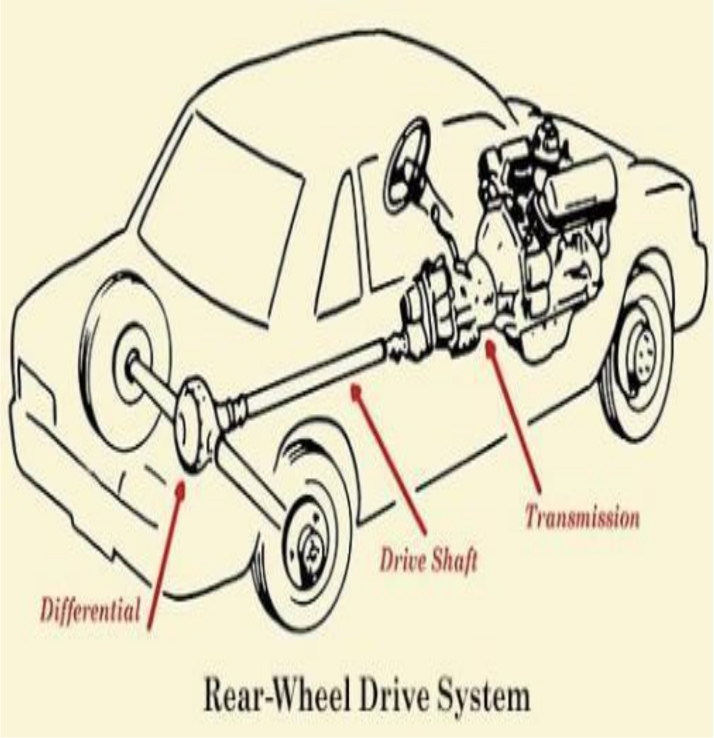


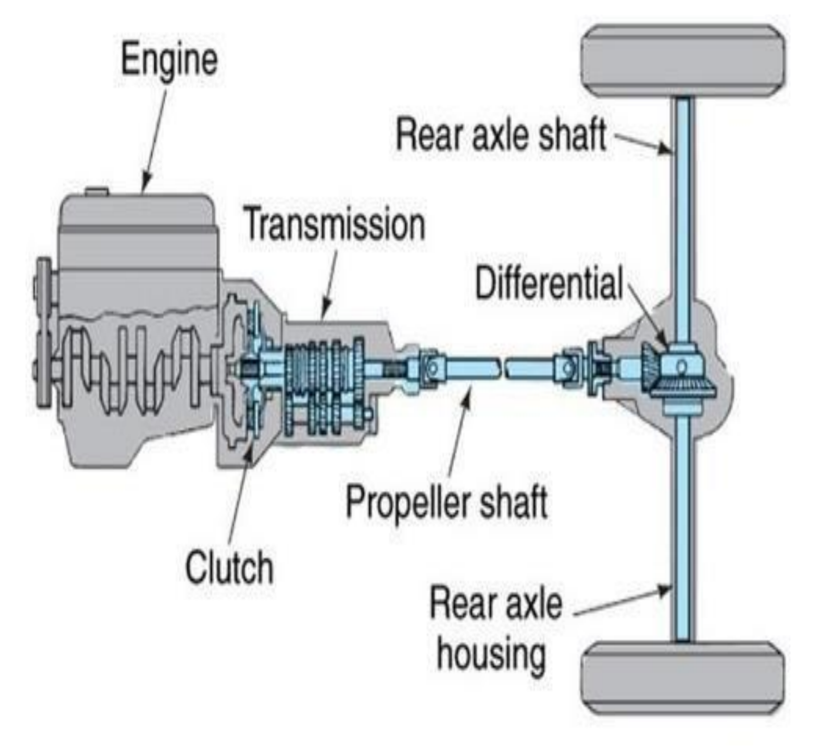
Power Drivetrains:



A) Rear-wheel drive (RWD)

- Power is transferred to the rear wheels to move the car
- This arrangement have many benefits over the front-wheel drive.
- It distributes weight more equally to each tire, which in turn provides better steering and handling.
- Offer superior braking compared to front-wheel drive vehicles.
- Rear-wheel drivetrain split the jobs of steering and driving the vehicle, lead to better handling and acceleration.
- Back wheels only have to move the car, In front-wheel the wheels have to both move the car forwards or backwards *and* steer it left or right.
- Examples : Lexus IS Series and the BMW 3 Series.





- Rear-wheel drivetrains consist of the following main parts:

a) **Transmission** : It controls the amount of power that goes from your engine to your wheels. In rear-wheel drive cars, the transmission is attached to the rear of the engine by way of a flywheel. The transmission takes the spinning movement — the torque — from the engine's crankshaft and passes it along.

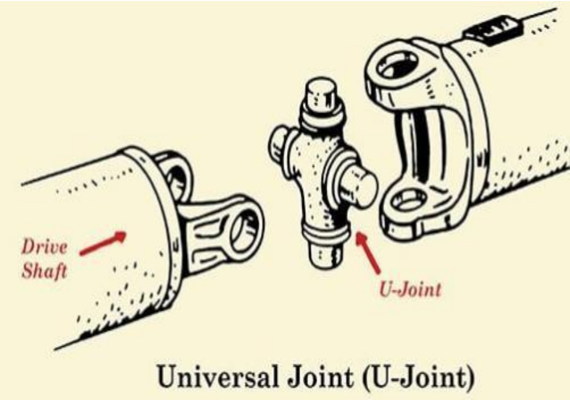
b) **Drive Shaft**. : The drive shaft is a spinning tube that connects to the rear of the transmission and transmits the spinning power that began in the engine to the back of the vehicle at the differential. Drive shaft designs come in two types: torque tube and Hotchkiss

Torque tube drive shafts were used on older vehicles and are still used on some trucks and SUVs today. The driveshaft itself is *enclosed* in a tube. Torque tubes connect the transmission and differential via a single universal joint, or U-joint for short.

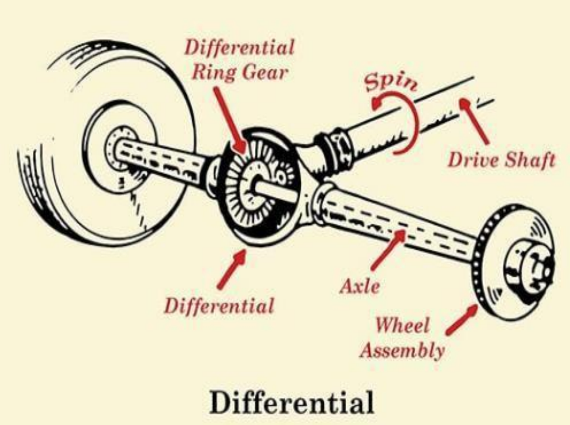
Hotchkiss drive shafts are the more common drive shaft design. Hotchkiss drive shafts have an open design, meaning you can actually see the drive shaft spin beneath your car when it's moving. Also, instead of just using one U-joint to connect the transmission and the differential, Hotchkiss drive shafts use two U-joints.

c) **Differential:** The differential is the melon-sized part that sits between the two rear wheels. It's the last stop along the drivetrain before torque is transferred to the rear wheels. The differential transfers torque, causing them to spin, which in turn moves the car.

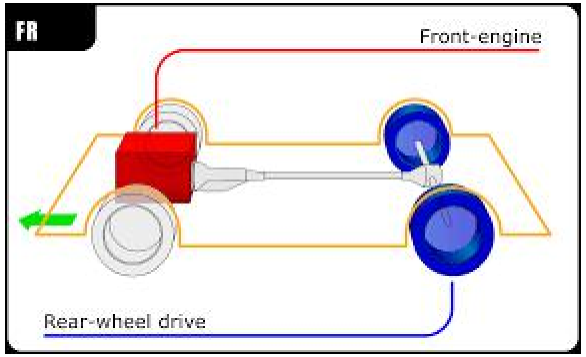
It's called a "differential" because it allows the two rear wheels on the same axle to move at *different* speeds. If there was a solid connection between both wheels, one of the wheels would need to skid in order for the axle to keep moving.



Universal Joint (U-Joint)

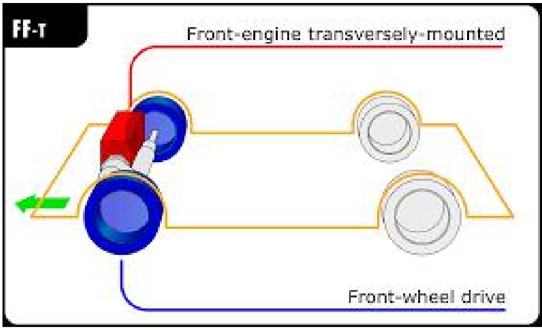


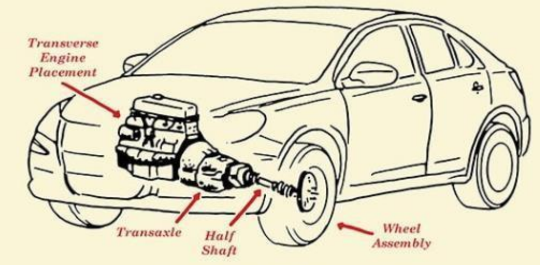
Differential



B) Front-wheel drive (FWD)

- All the components of the drive train — transmission, differential, and drive shafts — are in the front of the car. To fit all these components in the front, cars with a front-wheel drivetrain arrangement place the engine sideways in the car. This is called a “transverse engine placement.”
- Because all the parts of a forward-wheel drivetrain are positioned at the front of a vehicle, you can make them smaller and lighter. Or you can make the cars bigger, but just have more room for passengers. Consequently, most minivans use front-wheel drive.
- Another benefit of front-wheel drive vehicles is that because there’s more weight at the front of the vehicle due to all the components of the drivetrain being in the front, it provides more traction on slippery surfaces, like snow.





Front-Wheel Drive System

- Examples of vehicles with FWD include the Toyota Camry and the Honda Accord.

1.Transaxle

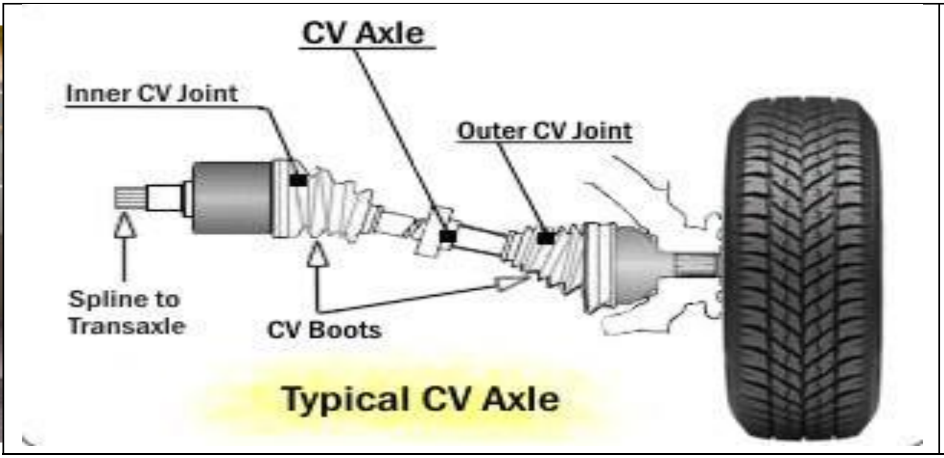
✓A transaxle combines the transmission and differential into one single unit.

2. **Half-shaft.**

✓Front-wheel drive vehicles don’t need long drive shafts to transfer torque to the wheels. Instead, a half-shaft connects from the transaxle to the wheel assembly.

✓In place of U-joints, half-shafts connect the transaxle and the wheel assembly with constant velocity joints, or CV-joints.

✓ CV-joints use a ball bearing mechanism to reduce friction and allow for the more complex wheel movements

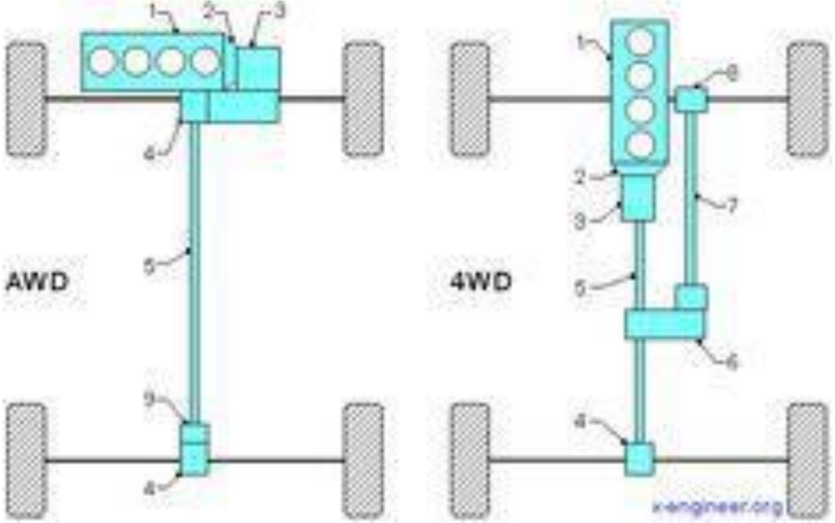


C) All-wheel drive (AWD)

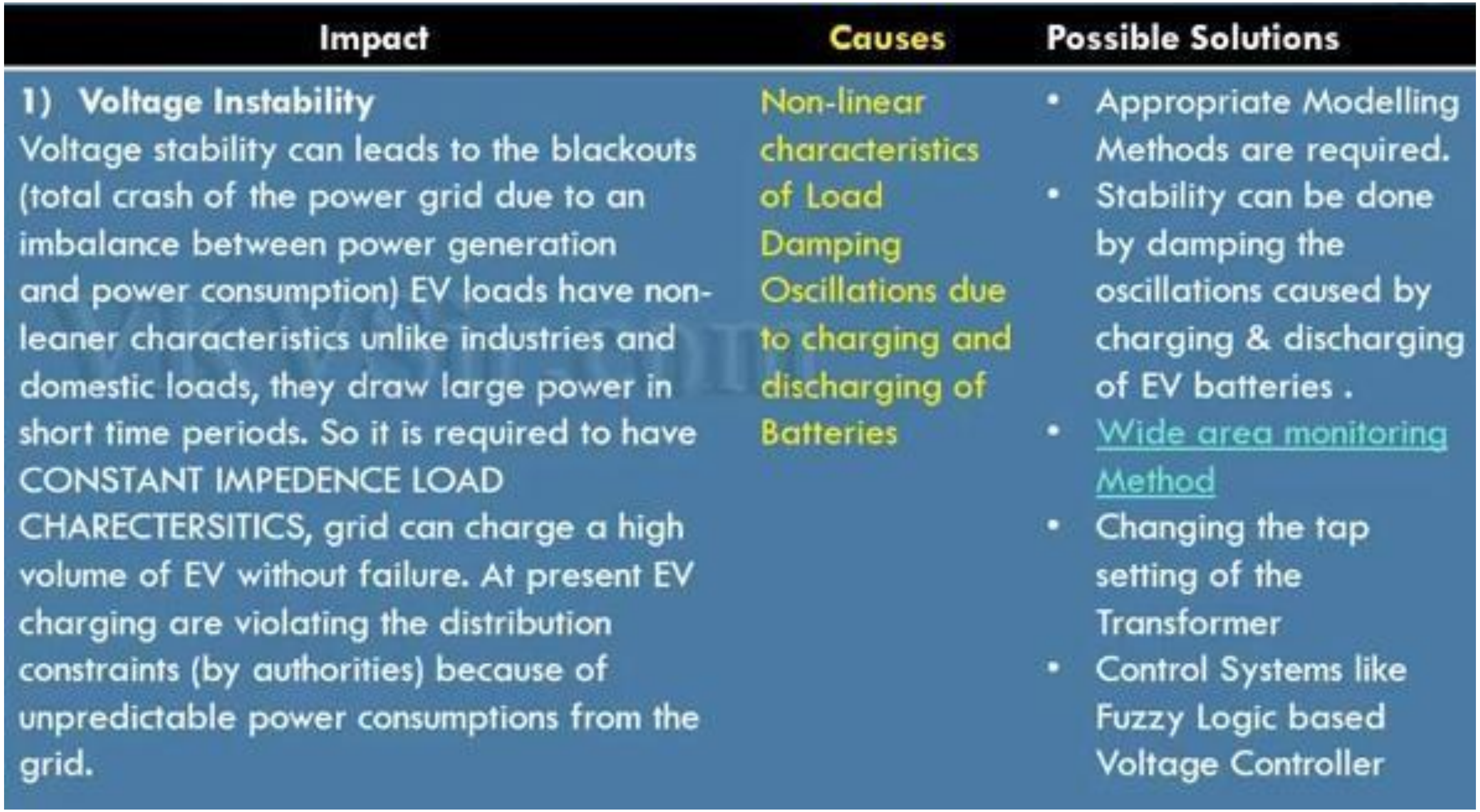
- The all-wheel drivetrain system has fluid-filled differentials and advanced electronics enabling the engine to send power to all four wheels. This provides a vast and highly improved capability for driving on wet or slippery roads.
- Examples of vehicles with AWD include the Subaru Legacy and the Acura RL.

D) Four-wheel drive (4WD)

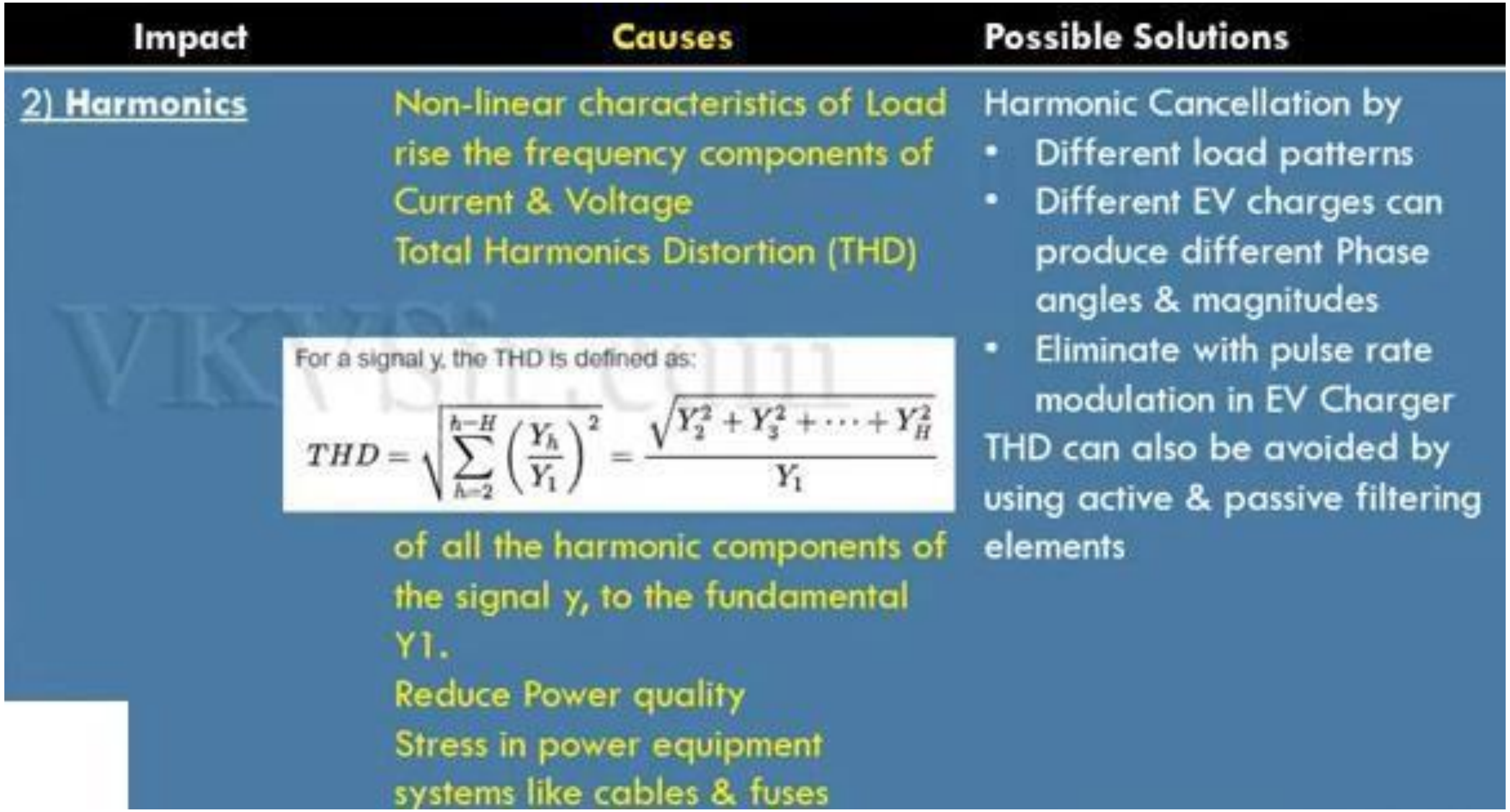
- The four-wheel drivetrain is similar to AWD in that the engine’s power is sent to all four wheels. However, 4WD is typically more robust because it’s designed to handle off-road driving.
- Examples of vehicles with 4WD include the Range Rover or the Ford F150.



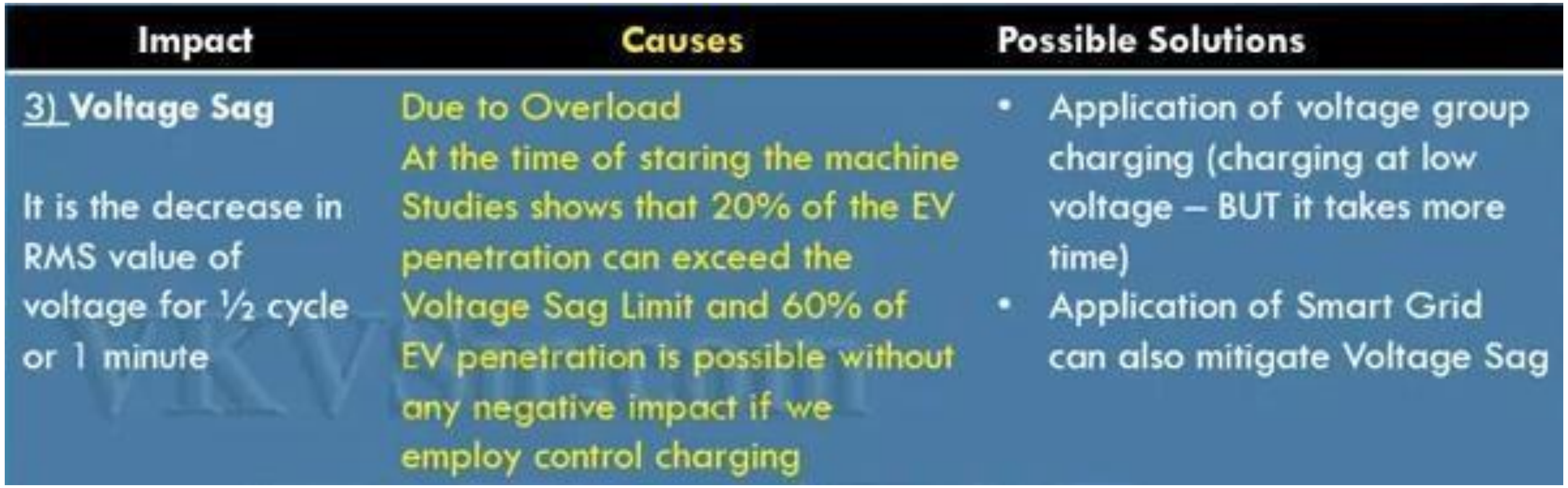
Impact of Modern Drive-Trains on Energy Supplies



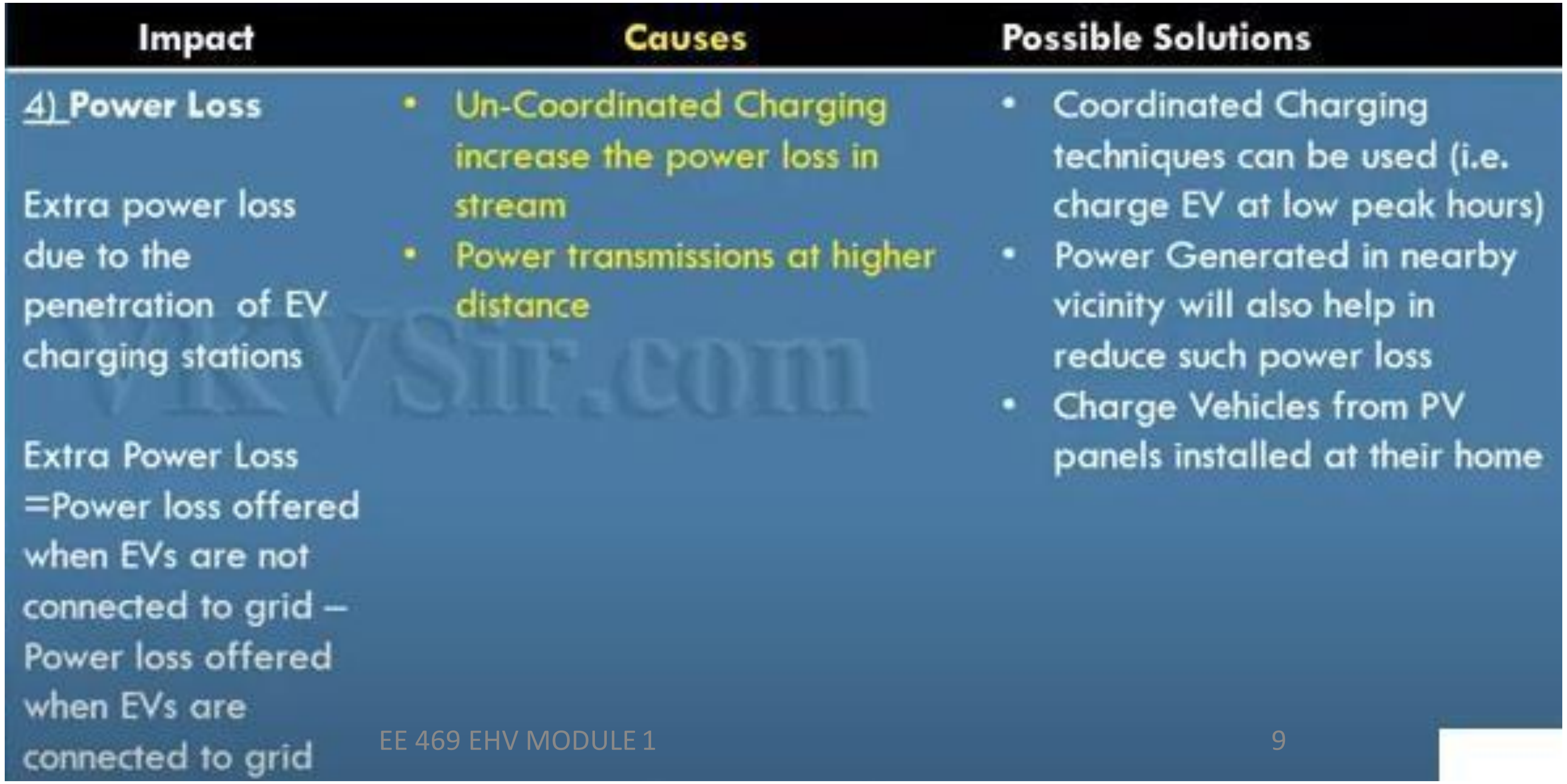
Impact	Causes	Possible Solutions
1) Voltage Instability Voltage stability can leads to the blackouts (total crash of the power grid due to an imbalance between power generation and power consumption) EV loads have non-leaner characteristics unlike industries and domestic loads, they draw large power in short time periods. So it is required to have CONSTANT IMPEDENCE LOAD CHARECTERSITICS, grid can charge a high volume of EV without failure. At present EV charging are violating the distribution constraints (by authorities) because of unpredictable power consumptions from the grid.	Non-linear characteristics of Load Damping Oscillations due to charging and discharging of Batteries	• Appropriate Modelling Methods are required. • Stability can be done by damping the oscillations caused by charging & discharging of EV batteries . • Wide area monitoring Method • Changing the tap setting of the Transformer • Control Systems like Fuzzy Logic based Voltage Controller



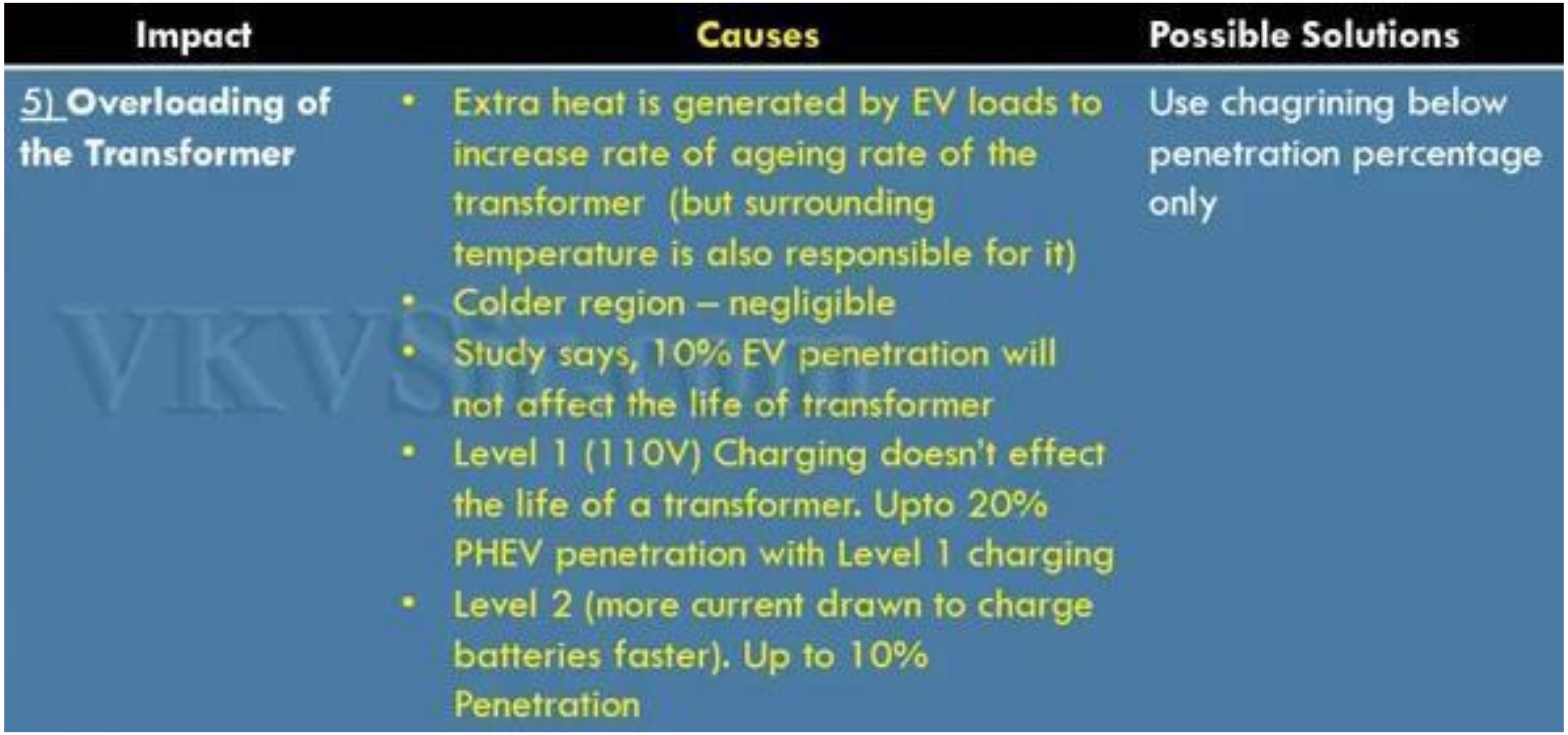
Impact	Causes	Possible Solutions
2) Harmonics	Non-linear characteristics of Load rise the frequency components of Current & Voltage Total Harmonics Distortion (THD) For a signal y, the THD is defined as: $THD = \sqrt{\sum_{h=2}^{h=H}\left(\frac{Y_h}{Y_1}\right)^2} = \frac{\sqrt{Y_2^2+Y_3^2+\cdots+Y_H^2}}{Y_1}$ of all the harmonic components of the signal y, to the fundamental Y1. Reduce Power quality Stress in power equipment systems like cables & fuses	Harmonic Cancellation by • Different load patterns • Different EV charges can produce different Phase angles & magnitudes • Eliminate with pulse rate modulation in EV Charger THD can also be avoided by using active & passive filtering elements



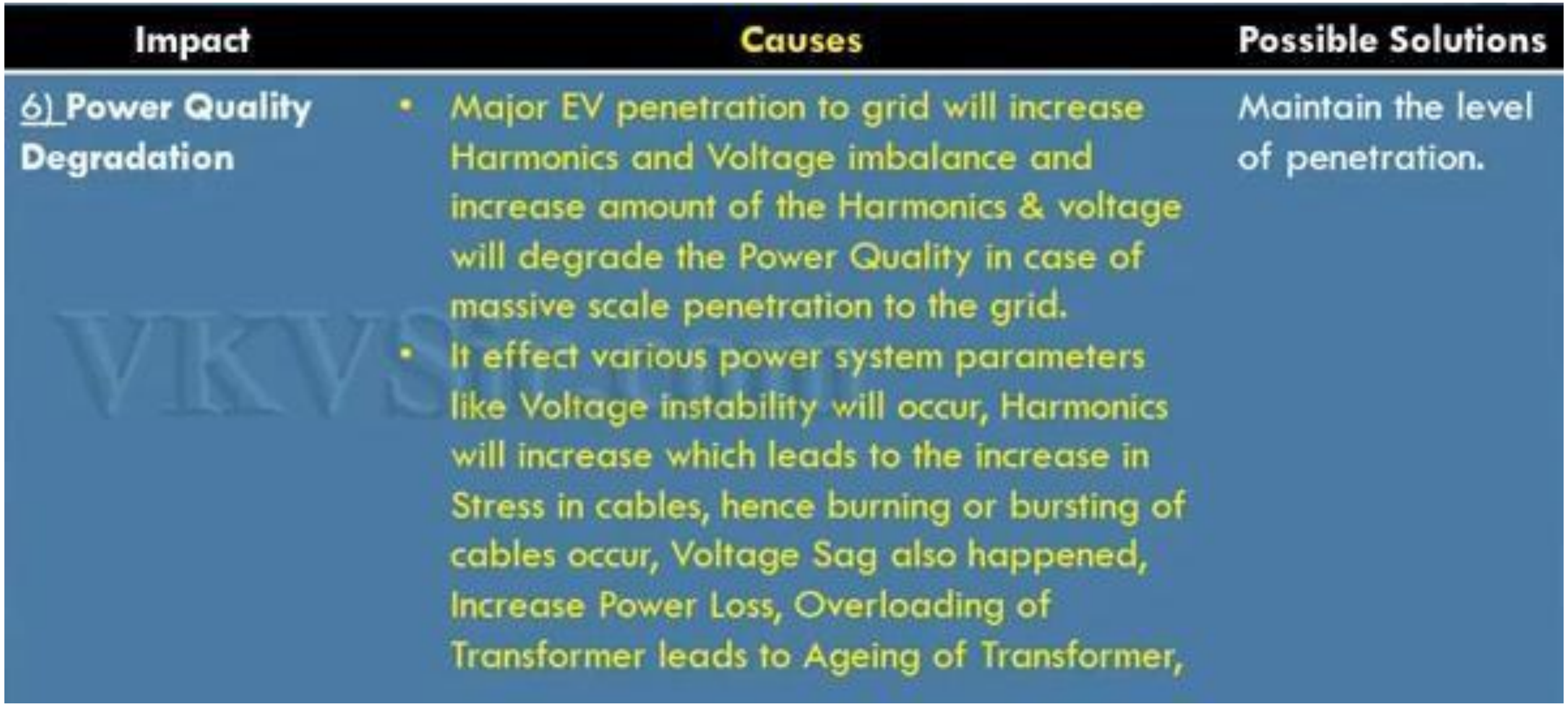
Impact	Causes	Possible Solutions
3) **Voltage Sag** It is the decrease in RMS value of voltage for ½ cycle or 1 minute	Due to Overload At the time of staring the machine Studies shows that 20% of the EV penetration can exceed the Voltage Sag Limit and 60% of EV penetration is possible without any negative impact if we employ control charging	• Application of voltage group charging (charging at low voltage – BUT it takes more time) • Application of Smart Grid can also mitigate Voltage Sag



Impact	Causes	Possible Solutions
4) **Power Loss** Extra power loss due to the penetration of EV charging stations Extra Power Loss =Power loss offered when EVs are not connected to grid – Power loss offered when EVs are connected to grid	• Un-Coordinated Charging increase the power loss in stream • Power transmissions at higher distance	• Coordinated Charging techniques can be used (i.e. charge EV at low peak hours) • Power Generated in nearby vicinity will also help in reduce such power loss • Charge Vehicles from PV panels installed at their home



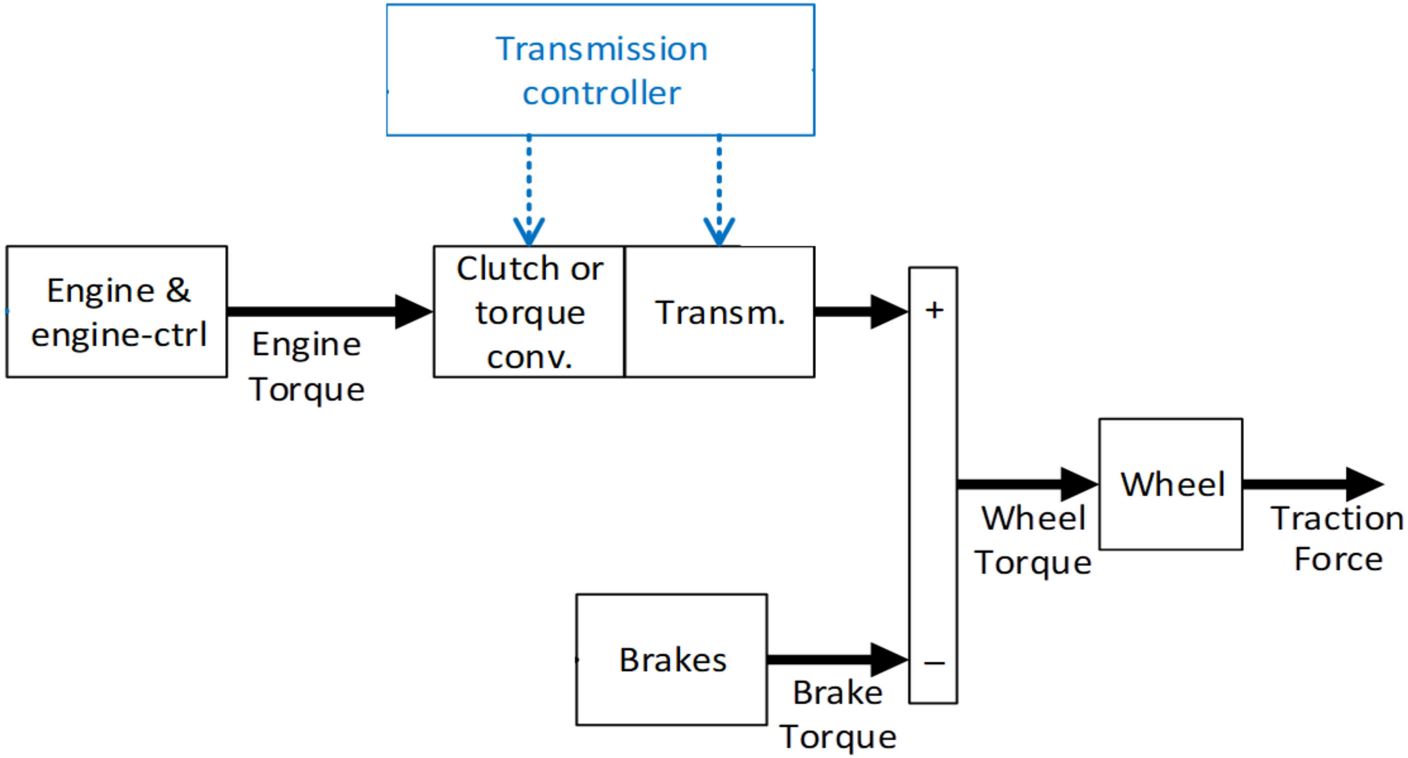
Impact	Causes	Possible Solutions
5) **Overloading of the Transformer**	• Extra heat is generated by EV loads to increase rate of ageing rate of the transformer (but surrounding temperature is also responsible for it) • Colder region – negligible • Study says, 10% EV penetration will not affect the life of transformer • Level 1 (110V) Charging doesn't effect the life of a transformer. Upto 20% PHEV penetration with Level 1 charging • Level 2 (more current drawn to charge batteries faster). Up to 10% Penetration	Use chagrining below penetration percentage only



Impact	Causes	Possible Solutions
6) **Power Quality Degradation**	- Major EV penetration to grid will increase Harmonics and Voltage imbalance and increase amount of the Harmonics & voltage will degrade the Power Quality in case of massive scale penetration to the grid. - It effect various power system parameters like Voltage instability will occur, Harmonics will increase which leads to the increase in Stress in cables, hence burning or bursting of cables occur, Voltage Sag also happened, Increase Power Loss, Overloading of Transformer leads to Ageing of Transformer,	Maintain the level of penetration.

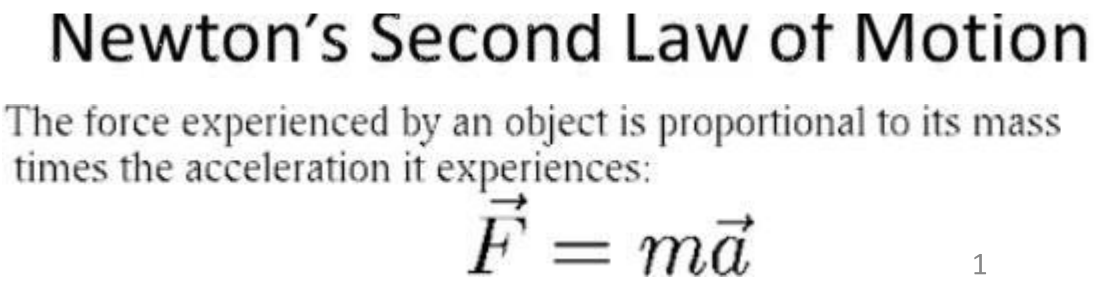
Transmission Systems

- *A transmission system manages the output torque and power of the engine and sends it to the drive wheels through a number of gears or drive-ratios.*
- This system connects to the engine through a flywheel, a heavy disk used to make the rotational output speed of the engine uniform.
- The engine only provides a limited range of torques and speeds, which is insufficient for some working conditions such as starting, stopping, acceleration, or deceleration.
- Essentially, the engine provides speed and torque up to a certain value, while the wheel road speeds and moving torque amount vary, based on driving and load condition:



Fundamentals of Vehicle Design

- The fundamentals of vehicle design involve the basic principles of physics, specially the ***Newton's second law of motion***.
- According to ***Newton's second law the acceleration of an object is proportional to the net force exerted on it***.
- Hence, an object accelerates when the net force acting on it is not zero.
- In a vehicle several forces act on it and the net or resultant force governs the motion according to the Newton's second law.
- The propulsion unit of the vehicle delivers the force necessary to move the vehicle forward.
- This force of the propulsion unit helps the vehicle to overcome the **resisting forces due to gravity, air and tire resistance**.



Newton's Second Law of Motion

The force experienced by an object is proportional to its mass times the acceleration it experiences:

$$\vec{F} = m\vec{a}$$

- The acceleration and speed of the vehicle depend on the
    - the power delivered by the propulsion unit
    - the road conditions
    - the aerodynamics of the vehicle
    - the composite mass of the vehicle, including the propulsion unit, all mechanical and electrical components, and the batteries.

General Description of Vehicle Movement

- The vehicle motion can be completely determined by analyzing the forces acting on it in the direction of motion.
- The forces acting on a vehicle, moving up a grade, are shown in Figure 1
- The force from the propulsion unit, which can be an electric motor or an IC engine or a combination of the two, is known as ***tractive force*, $\mathbf{F_t}$.**
- The *tractive force* ($\mathbf{F_t}$) in the contact area between the tires of the driven wheels and the road surface propels the vehicle forward.
- The ***tractive force*** ($\mathbf{F_t}$) is produced by the power plant and transferred to the driving wheels via the transmission and the final drive.

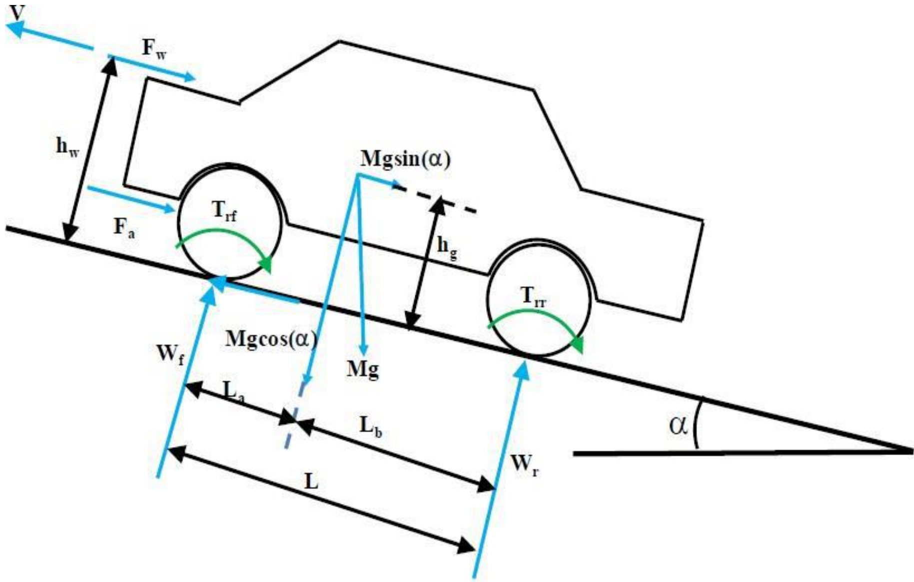


Figure 1: Forces acting on a vehicle going uphill [1]

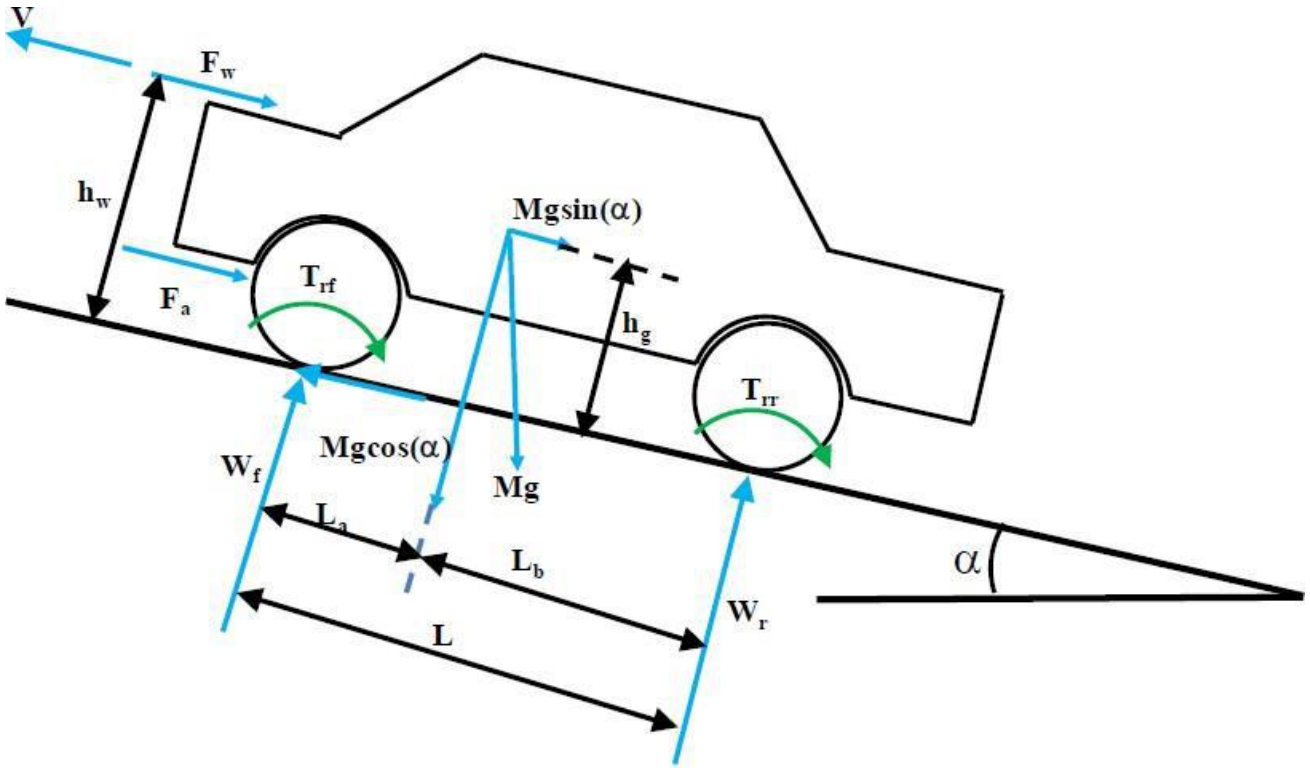
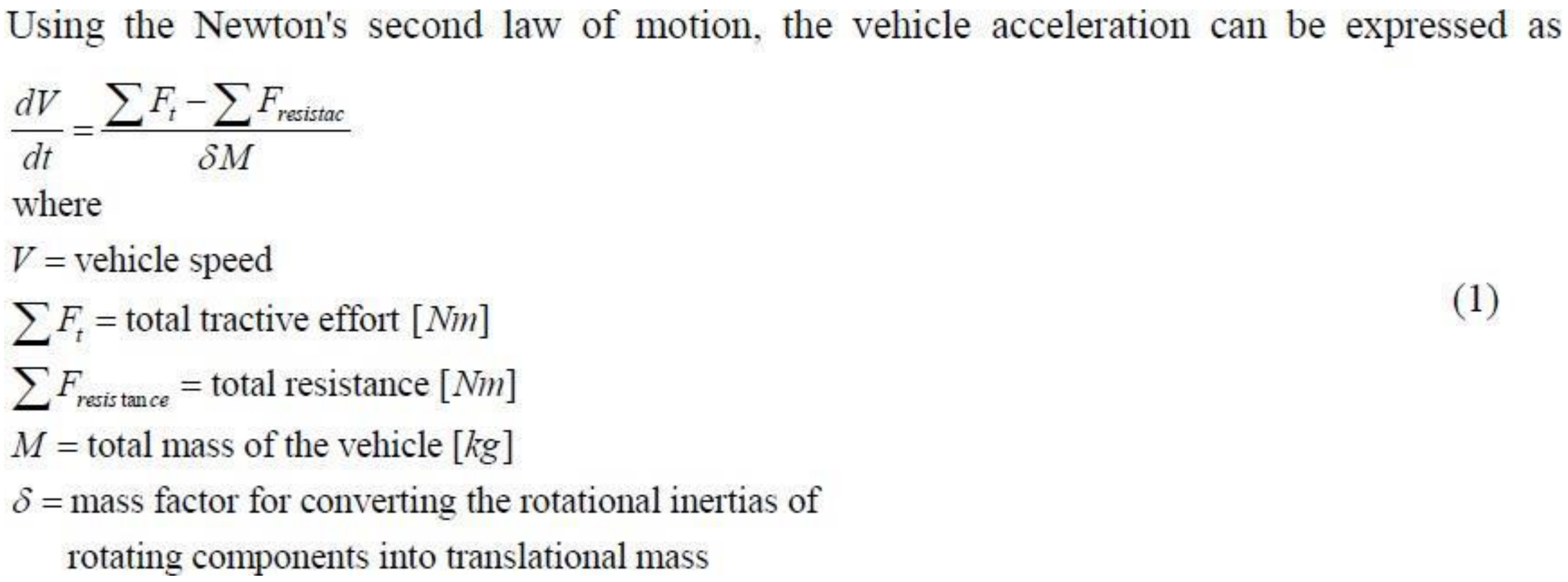


Figure 1: Forces acting on a vehicle going uphill [1]

- When the vehicle moves, it encounters a resistive force that tries to retard its motion. The resistive forces are
  - *Rolling resistance*
  - *Aerodynamic drag*
  - *Uphill resistance / Grading resistance*


Using the Newton's second law of motion, the vehicle acceleration can be expressed as

$$\frac{dV}{dt} = \frac{\sum F_t - \sum F_{resistac}}{\delta M} \qquad (1)$$

where

V = vehicle speed

$\sum F_t$ = total tractive effort $[Nm]$

$\sum F_{resistance}$ = total resistance $[Nm]$

M = total mass of the vehicle $[kg]$

δ = mass factor for converting the rotational inertias of rotating components into translational mass

- When the vehicle moves, it encounters a resistive force that tries to retard its motion. The resistive forces are
  - ***Rolling resistance***
  - ***Aerodynamic drag***
  - ***Uphill resistance / Grading resistance***

Mathematical Models to Describe Vehicle Performance

- The first step in vehicle performance modelling is to produce an equation for the tractive effort.
- This is the force propelling the vehicle forward, transmitted to the ground through the drive wheels.
- Consider a vehicle of mass M, proceeding at a velocity V, up a slope of angle α, as in Figure1.
- The force propelling the vehicle forward, the tractive effort, has to accomplish the following:
    - Overcome the vehicle resistances
        - **Rolling resistance**
        - **Aerodynamic drag**
        - Provide the force needed to overcome the component of the vehicle's weight acting down the slope. **(Uphill resistance / Grading resistance / Hill climbing force)**
        - Accelerate the vehicle, if the velocity is not constant; *If the velocity of the vehicle is changing, then clearly a force will need to be applied in addition to the resistive forces.* **(Acceleration force / Acceleration resistance)**

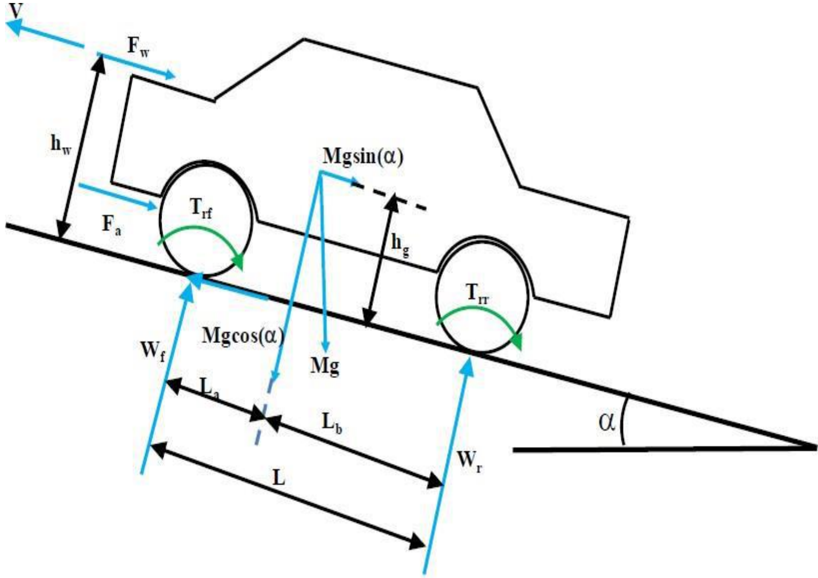


Figure 1: Forces acting on a vehicle going uphill [1]

Vehicle Resistance

- As shown in Figure 1, vehicle resistance opposing its movement includes
  - ***Rolling Resistance,*** $\mathbf{F_r}$ of the tires, appearing in Figure 1 as rolling resistance torque T_{rf} and T_{rr},
  - ***Aerodynamic Drag***, $\mathbf{F_w}$, and
  - ***Grading Resistance*** $\mathbf{F_g}$ (the $M g \sin \alpha$ in Figure 1)

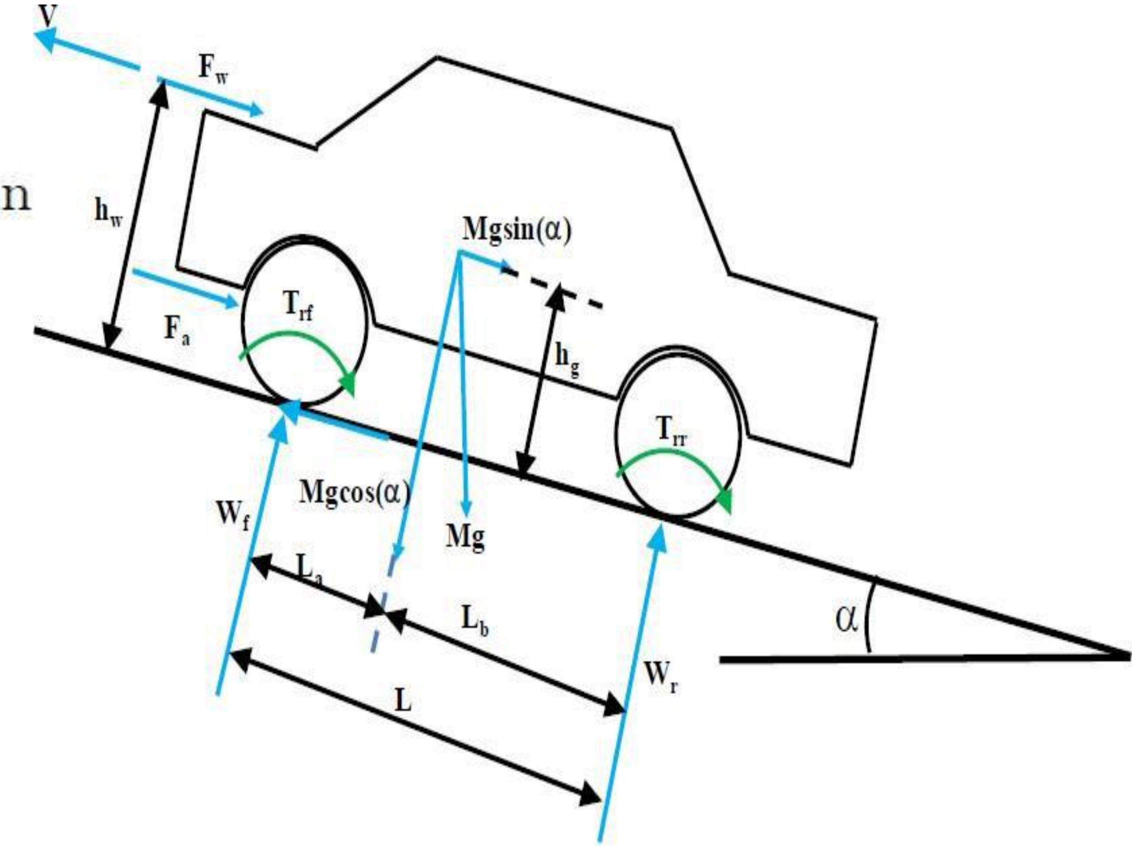


Figure 1: Forces acting on a vehicle going uphill [1]

Rolling Resistance Force

- The *rolling resistance* is primarily due to the ***friction of the vehicle tyre on the road.***
- Friction in bearings and the gearing system also play their part.
- The rolling resistance is approximately constant, and hardly depends on vehicle speed.
- It is proportional to vehicle weight. The equation is:

$$F_r = f_r M g$$

  - where f_r *is the coefficient of rolling resistance*.

- The main factors controlling f_r are the ***type of tyre and the tyre pressure***.
- Any cyclist will know this very well; the free-wheeling performance of a bicycle becomes much better if the tyres are pumped up to a high pressure, though the ride may be less comfortable.

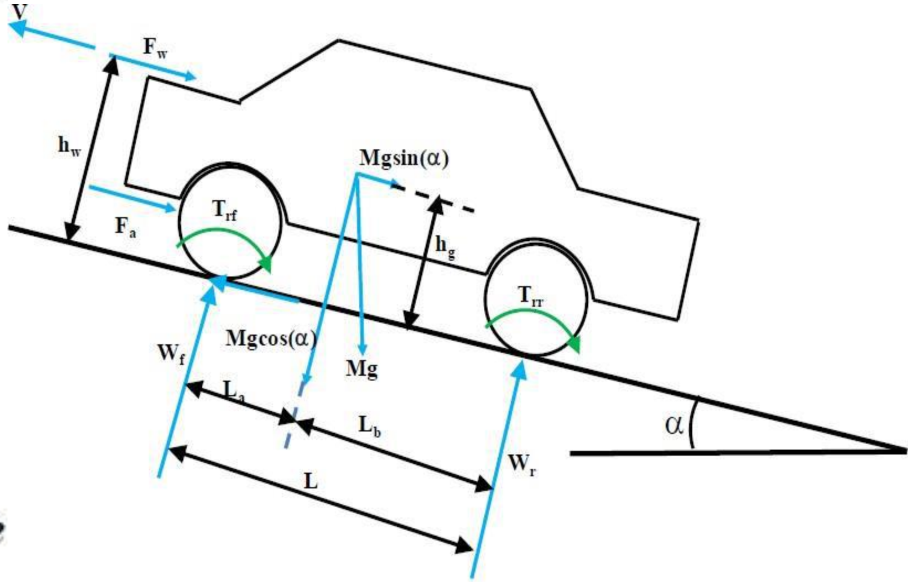


Figure 1: Forces acting on a vehicle going uphill [1]

Rolling Resistance cont.

- The rolling resistance of tires on hard surfaces is due to hysteresis in the tire material. This is due to the deflection of the carcass while the tire is rolling.
- In **Figure 2** a tire at standstill is shown.
- On this tyre a force (**P**), is acting at its centre.
- The pressure in the contact area between the tire and the ground is distributed symmetrically to the centre line and the resulting *reaction force* ($\mathbf{P_z}$) is aligned along **P**.

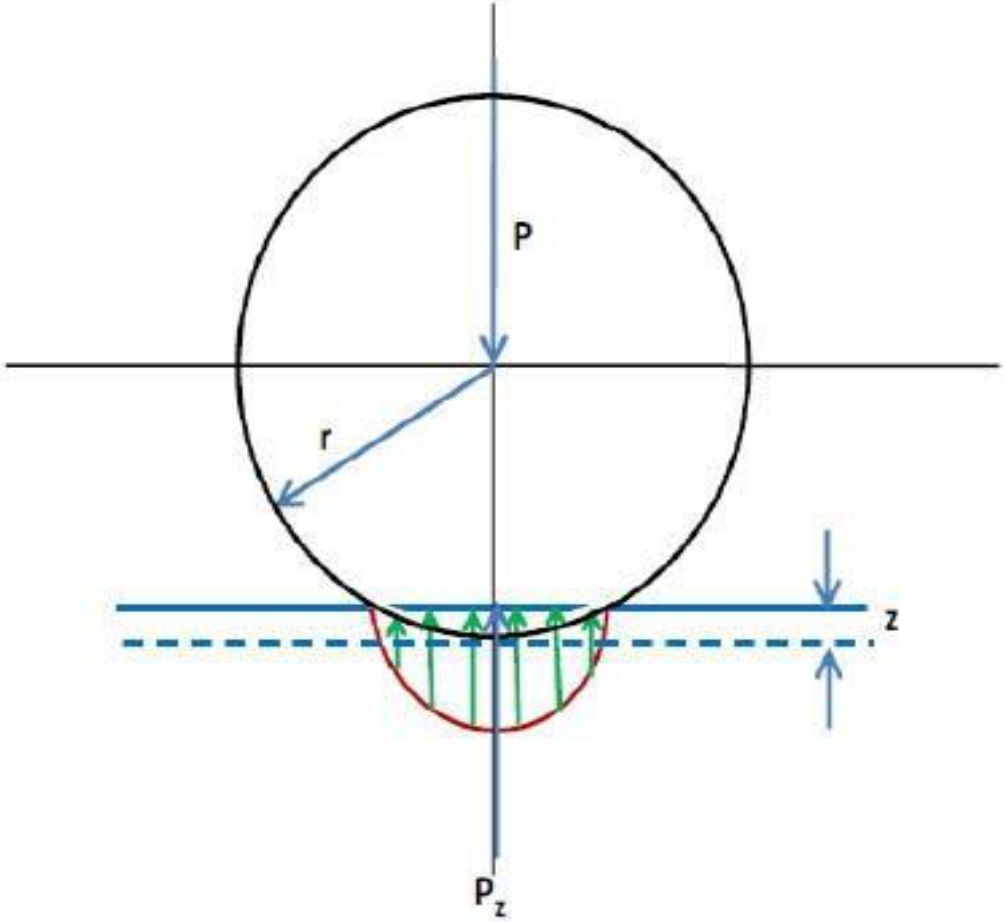
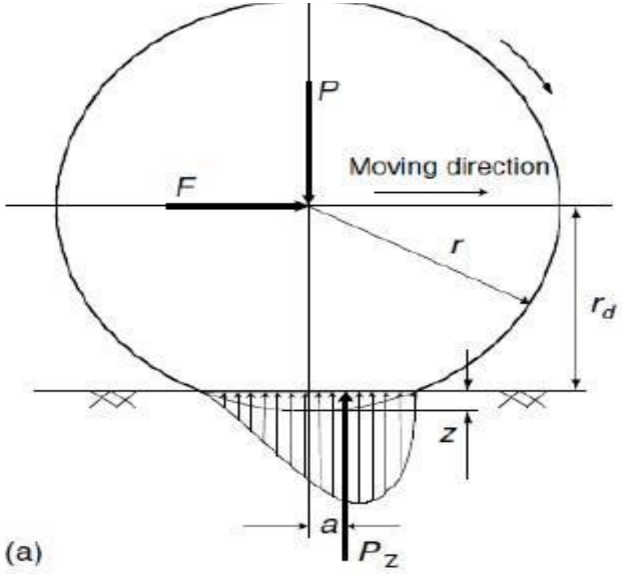


Figure 2: Pressure distribution in contact area

- The scenario of a rolling tire is shown in **Figure 4**.
- When the tire rolls, the leading half of the contact area is loading and the trailing half is unloading.
- Thus, the pressure on the leading half is greater than the pressure on the trailing half (**Figure 4a**).
- This phenomenon results in the ground reaction force shifting forward.
- The shift in the ground reaction force creates a moment that opposes rolling of the wheels.
- On soft surfaces, the rolling resistance is mainly caused by deformation of the ground surface, (**Figure 4b**).
- In this case the ground reaction force almost completely shifts to the leading half.



gure 4a: Force acting on a tyre vs. deformation
in loading and unloading on a hard surface

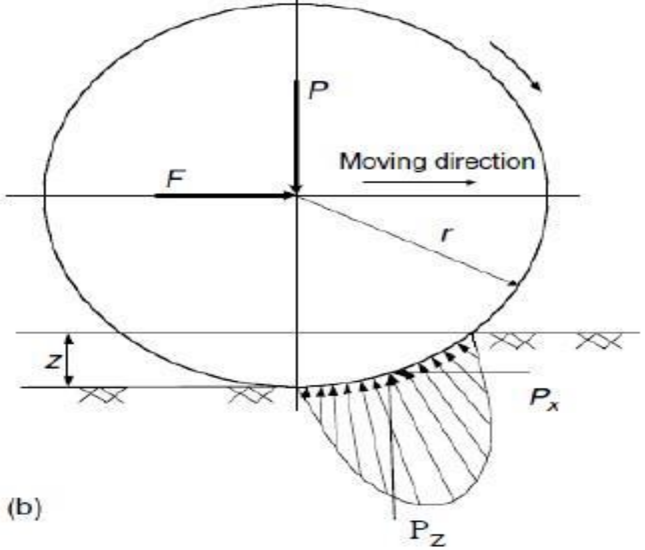


Figure 4b: Force acting on a tyre vs. deformation
in loading and unloading on a soft surface

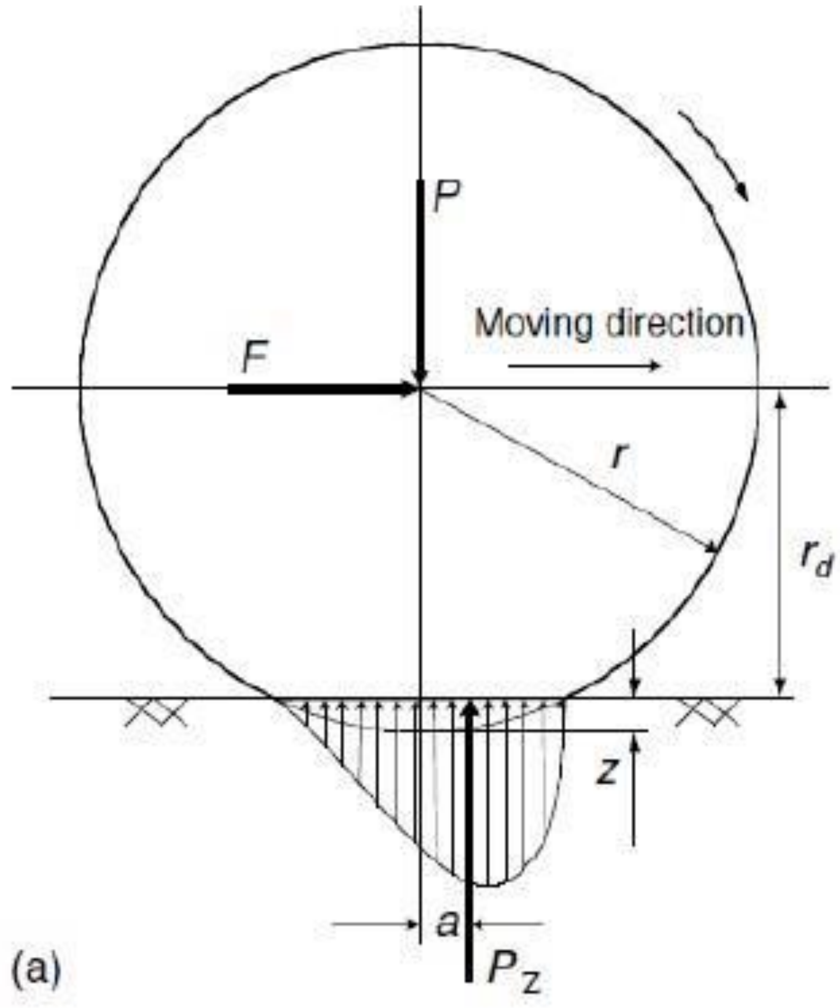


Figure 4a: Force acting on a tyre vs. deformation
In loading and unloading on a hard surface

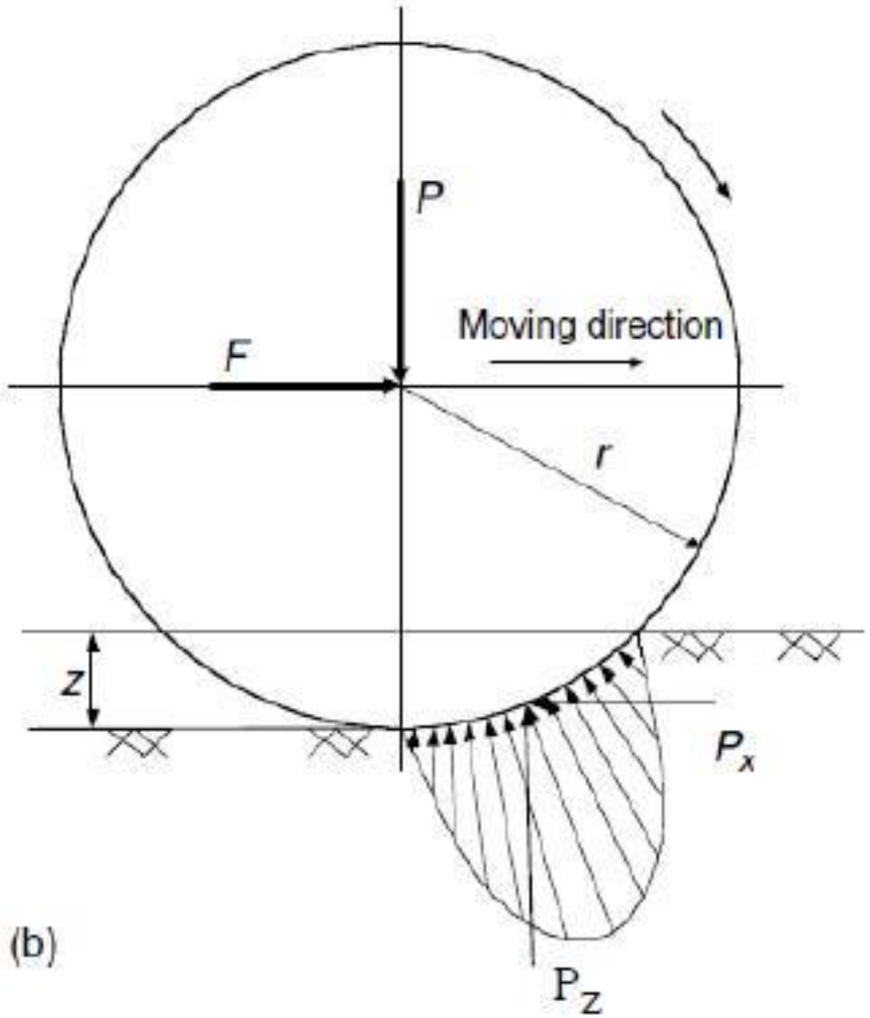


Figure 4b: Force acting on a tyre vs. deformation
in loading and unloading on a soft surface

- The moment produced by forward shift of the resultant ground reaction force is called rolling resistance moment (**Figure 4a**) and can be expressed as

$$T_r = Pa = Mga \qquad \text{--- (2)}$$

where

T_r = rolling resistance $[Nm]$

P = Normal load acting on the centre of the rolling wheel $[N]$

M = mass of the vehicle $[kg]$

g = acceleration constant $[m/s^2]$

a = deformation of the tyre $[m]$

- To keep the wheel rolling, a force **F**, acting on the centre of the wheel is required to balance this rolling resistant moment. This force is expressed as

$$F = \frac{T_r}{r_d} = \frac{Pa}{r_d} = Pf_r \qquad \text{--- (3)}$$

- Where r_d is the effective radius of the tire and
- $f_r = \frac{a}{r_d}$ is called the rolling resistance coefficient.

- In this way, the rolling resistant moment can be equivalently replaced by a horizontal force acting on the wheel center in the opposite movement direction of the wheel.

- This equivalent force is called the ***rolling resistance*** and its magnitude is given by

$$F_r = P f_r \qquad \text{--- (4)}$$

where

P = Normal load acting on the centre of the rolling wheel [N]

f_r = rolling resistance coefficient

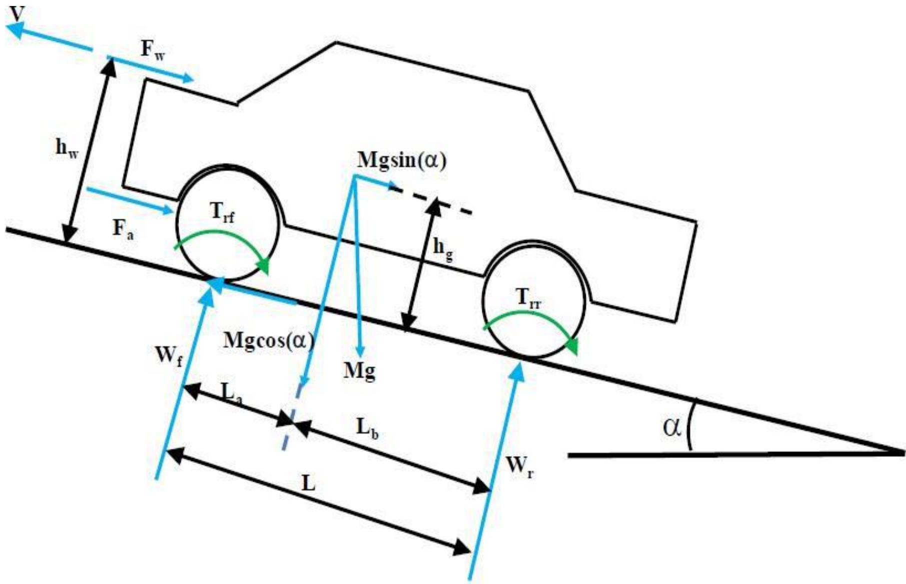


Figure 1: Forces acting on a vehicle going uphill [1]

- When a vehicle is moving up a gradient, the normal force (**P**), in **equation 4**, is replaced by the component that is perpendicular to the road surface. Hence, **equation 4** is rewritten as

$$F_r = Pf_r \cos(\alpha) = Mgf_r \cos(\alpha) \quad \text{--- (5)}$$

where

P = Normal load acting on the centre of the rolling wheel $[N]$

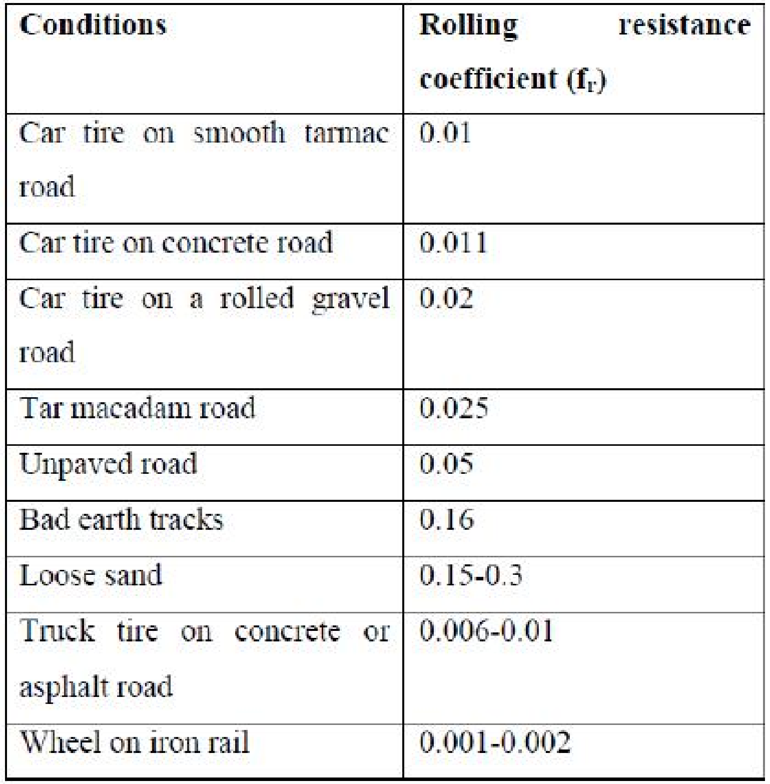
f_r = rolling resistance coefficient

α = road angle $[radians]$

- The value of $\mathbf{f_r}$ can reasonably readily be found by pulling a vehicle at a steady very low speed, and measuring the force required.

- Typical values of $\mathbf{f_r}$ are 0.015 for a radial ply tyre, down to about 0.005 for tyres developed especially for electric vehicles.

- The rolling resistance coefficient, **f_r**, is a function of:
  - tire material
  - tire structure
  - tire temperature
  - tire inflation pressure
  - tread geometry
  - road roughness
  - road material
  - presence of absence of liquids on the road



Conditions	**Rolling resistance coefficient (f_r)**
Car tire on smooth tarmac road	0.01
Car tire on concrete road	0.011
Car tire on a rolled gravel road	0.02
Tar macadam road	0.025
Unpaved road	0.05
Bad earth tracks	0.16
Loose sand	0.15-0.3
Truck tire on concrete or asphalt road	0.006-0.01
Wheel on iron rail	0.001-0.002

- The typical values of the rolling resistance coefficient (**f_r**) are given in **Table 1**.

- For fuel saving in recent years, low-resistance tires for passenger cars have been developed. Their rolling resistance coefficient is less than 0.01.

Aerodynamic Drag

- A ***vehicle traveling at a particular speed in air encounters a force resisting its motion*** (the force is due to the friction of the vehicle body moving through the air).

- This ***force is known as aerodynamic drag***.

- It mainly results from two components:

  - ***Shape Drag***

  - ***Skin Effect***

- The **shape drag** is due to the shape of the vehicle.
- 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.
- This results in high air pressure in the front of the vehicle.
- 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.
- Hence, the motion of the vehicle creates two zones of pressure.
- The high pressure zone in the front of the vehicle opposes its movement by pushing.
- On the other hand, the low pressure zone developed at the rear of the vehicle opposes its motion by pulling it backwards.
- The resulting force on the vehicle is the **shape drag**.

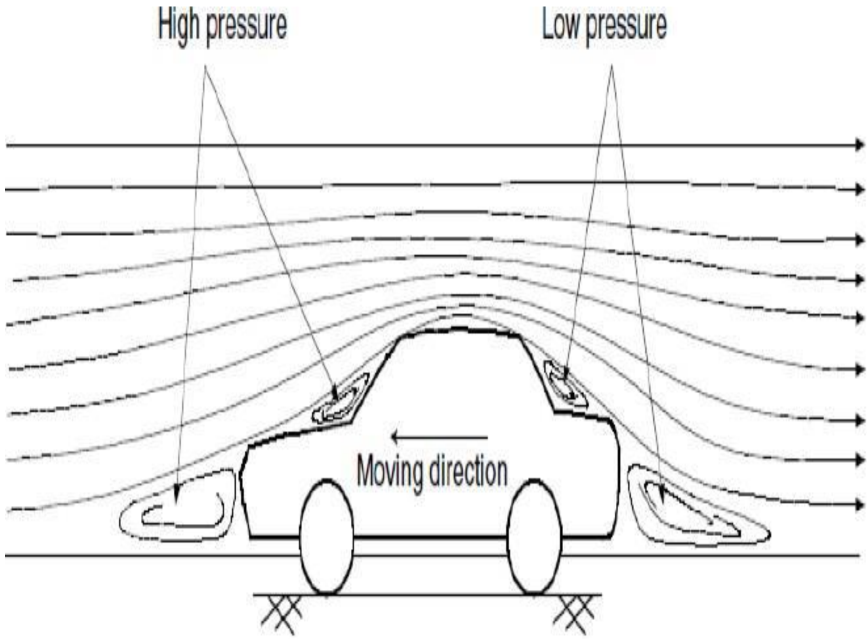
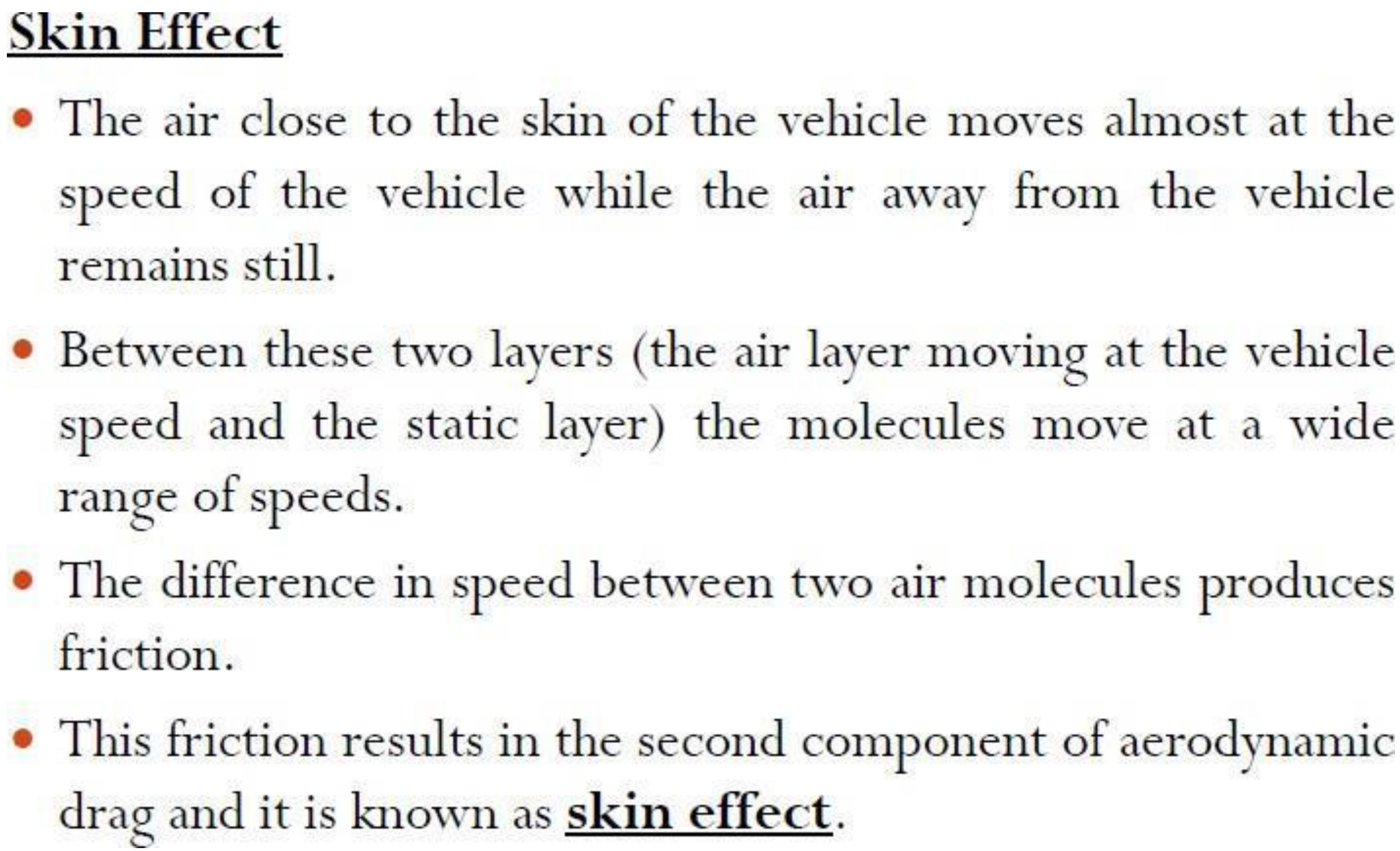


Figure 5. Shape drag



Skin Effect

- The air close to the skin of the vehicle moves almost at the speed of the vehicle while the air away from the vehicle remains still.
- Between these two layers (the air layer moving at the vehicle speed and the static layer) the molecules move at a wide range of speeds.
- The difference in speed between two air molecules produces friction.
- This friction results in the second component of aerodynamic drag and it is known as **skin effect**.

- *Aerodynamic drag is a function of vehicle speed V, vehicle frontal area A_f , shape of the vehicle, air density* $\boldsymbol{\rho}$, **protrusions such as side mirrors, ducts and air passages, spoilers, and many other factors.**

- The aerodynamic drag is expressed as

$$F_w = \frac{1}{2}\rho A_f C_D V^2 \qquad \text{--- (8)}$$

where

ρ = density of air $[kg/m^3]$

A_f = vehicle frontal area $[m^2]$

V = vehicle speed $[m/s]$

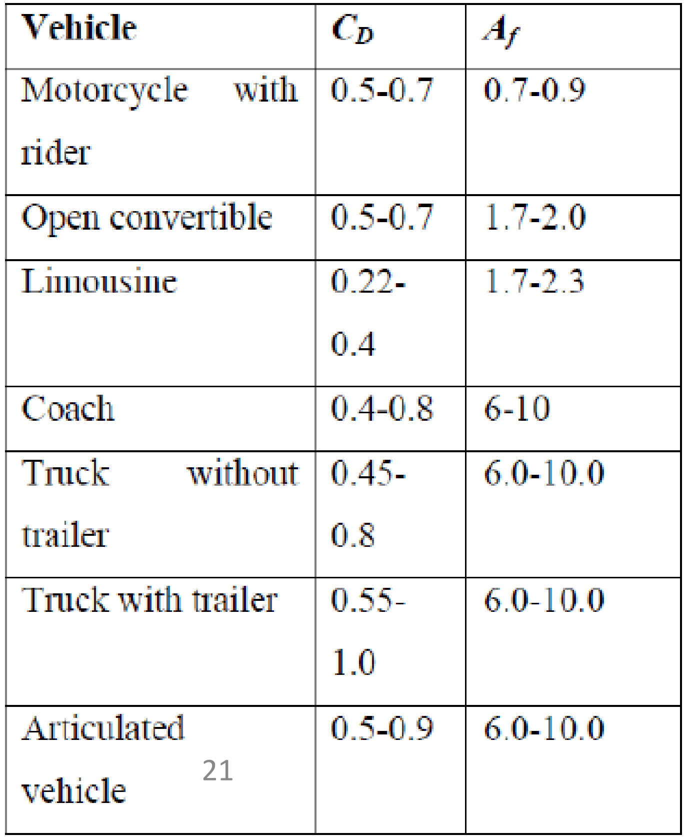
C_D = drag coefficient

- Aerodynamic drag can also be is expressed as

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

  - where 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 v body shapes are shown in Table 2.



Vehicle	C_D	A_f
Motorcycle with rider	0.5-0.7	0.7-0.9
Open convertible	0.5-0.7	1.7-2.0
Limousine	0.22-0.4	1.7-2.3
Coach	0.4-0.8	6-10
Truck without trailer	0.45-0.8	6.0-10.0
Truck with trailer	0.55-1.0	6.0-10.0
Articulated vehicle	0.5-0.9	6.0-10.0

- The drag coefficient C_D can be reduced by good vehicle design. A typical value for a saloon car is 0.3, but some electric vehicle designs have achieved values as low as 0.19.
- There is greater opportunity for reducing C_D in electric vehicle design because there is more flexibility in the location of the major components, and there is less need for cooling air ducting and under-vehicle pipework.
- However, some vehicles, such as motorcycles and buses will inevitably have much larger values, and C_D figures of around 0.7 are more typical in such cases.

- The density of air does of course vary with temperature, altitude and humidity. However a value of 1.25 kg m^3 is a reasonable value to use in most cases. Provided that SI units are used (m^2 for A, ms^{-1} for v) then the value of F_w will be given in Newtons.

Grading Resistance

- When a vehicle goes up or down a slope, its weight produces a component of force that is always directed downwards, **Figure 6**.
- This force component opposes the forward motion, i.e. the **grade climbing.**
- When the vehicle goes down the grade, this force component aids the vehicle motion **(grade descending).**
- In vehicle performance analysis, only uphill operation is considered.
- This grading force is usually called **grading resistance**.

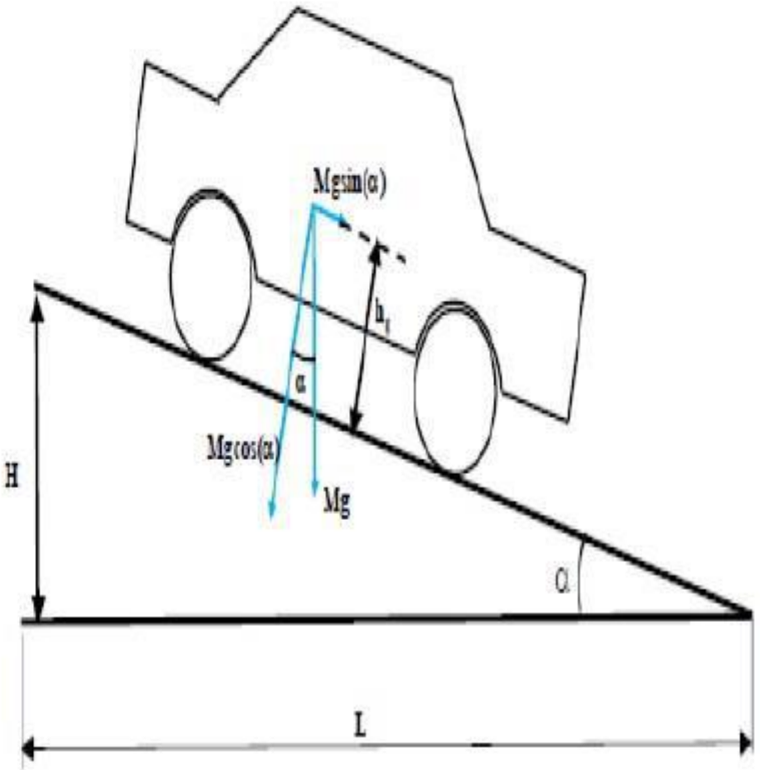


Figure 6: Vehicle going up a grade

- The grading resistance can be expressed as

$$F_g = Mg\sin(\alpha) \qquad \text{--- (9)}$$

where

M = mass of vehicle $[kg]$

g = acceleration constant $[m/s^2]$

α = road angle $[radians]$

- In order to simplify the calculation, the ***road angle*** $\boldsymbol{\alpha}$, is usually replaced by the ***grade value***, when the road angle is small. The grade value is defined as (**Figure 6**)

$$i = \frac{H}{L} = \tan(\alpha) \approx \sin(\alpha) \qquad \text{--- (10)}$$

- In some literature, the **tire rolling resistance** and the **grading resistance** taken together and is called **road resistance.**

- The road resistance is expressed as

$$F_{rd} = F_r + F_g = M\,g\,(f_r\cos(\alpha)+\sin(\alpha)) \qquad \text{--- (11)}$$

where

M = mass of vehicle $[kg]$

g = acceleration constant$[m/s^2]$

f_r = rolling resistance coefficient

- When the road angle is small, the road resistance can be simplified as

$$F_{rd} = F_r + F_g = M\,g\,(\,f_r+i\,)$$

Acceleration Resistance

- In addition to the driving resistance occurring in steady state motion, inertial forces also occur during acceleration and braking.
- The total mass of the vehicle and the inertial mass of those rotating parts of the drive accelerated or braked are the factors influencing the resistance to acceleration:

$$F_a = \left(M + \frac{\sum J_{rot}}{r_{dyn}^2} \right) \frac{dV}{dt} \qquad \text{--- (12)}$$

where

M = mass of vehicle $[kg]$

J_{rot} = intertia of rotational components $[kg \times m^2]$

V = speed of the vehicle $[km / h]$

r_{dyn} = *dynamic radius of the tyre* $[m]$

- The above equation for acceleration resistance can be simplified and written as

$$F_a = \lambda M \frac{dV}{dt} \qquad \text{--- (13)}$$

where

λ = rotational inertia constant

M = mass of the vehicle $[kg]$

V = speed of the vehicle $[m/s]$

Total Driving Resistance

The traction force (**F**$_t$) required at the drive wheels is made up of the driving resistance forces and is defined as

$$F_{resis\tan ce} = F_r + F_w + F_g + F_a \tag{14}$$

Substituting the values of all the forces in equation 14, gives

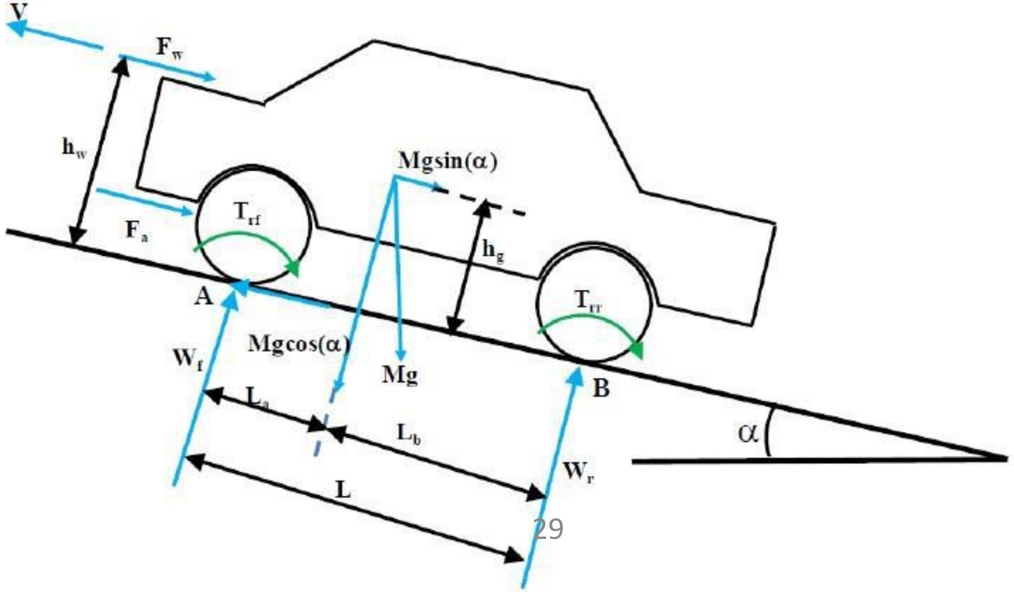
$$F_{resis\tan ce} = Mgf_r \cos(\alpha) + \frac{1}{2}\rho A_f C_D V^2 + Mg\sin(\alpha) + \lambda M\frac{dV}{dt} \tag{15}$$

The equation 15 may be used to calculate the power required (**P**$_{\mathbf{req}}$):

$$P_{req} = F_{resis\tan ce} V \tag{16}$$

Dynamic Equation

- In the longitudinal direction, the major external forces acting on a two axle vehicle (**Figure 1**) include:
  - Rolling resistance of the front and rear tires ($\mathbf{F_{rf}}$ and $\mathbf{F_{rr}}$), which are represented by rolling resistance moment, $\mathbf{T_{rf}}$ and $\mathbf{T_{rr}}$
  - Aerodynamic drag ($\mathbf{F_w}$)
  - Grade climbing resistance ($\mathbf{F_g}$)
  - Acceleration resistance ($\mathbf{F_a}$)
  - Tractive effort of the front and rear tires, $\mathbf{F_{tf}}$ and $\mathbf{F_{tr}}$. $\mathbf{F_{tf}}$ is zero for a rear-wheel-driven vehicle, whereas $\mathbf{F_{tr}}$ is zero for a front-wheel-driven vehicle



- The dynamic equation of vehicle motion along the longitudinal direction is expressed by

$$M\frac{dV}{dt} = \left(F_{tf} + F_{tr}\right) - \left(F_{rf} + F_{rr} + F_{w} + F_{g} + F_{a}\right) \qquad \text{--- } \mathbf{17}$$

  - where $\frac{dV}{dt}$ is the linear acceleration of the vehicle along the longitudinal direction and M is the vehicle mass.

- The first term on the right side is the total tractive effort and the second term is the total tractive resistance.

Using the Newton's second law of motion, the vehicle acceleration can be expressed as

$$\frac{dV}{dt} = \frac{\sum F_t - \sum F_{resistac}}{\delta M}$$

2.3 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 F_{rf} and F_{rr}, which are represented by rolling resistance moment T_{rf} and T_{rr}, aerodynamic drag F_w, grading resistance F_g ($M_v g \sin \alpha$), and tractive effort of the front and rear tires, F_{tf} and F_{tr}. F_{tf} is zero for a rear-wheel-driven vehicle, whereas F_{tr} is zero for a front-wheel-driven vehicle.

The dynamic equation of vehicle motion along the longitudinal direction is expressed by

$$M_v \frac{dV}{dt} = (F_{tf} + F_{tr}) - (F_{rf} + F_{rr} + F_w + F_g), \tag{2.13}$$

where dV/dt is the linear acceleration of the vehicle along the longitudinal direction and M_v is the vehicle mass. The first term on the right-hand side of (2.13) is the total tractive effort and the second term is the resistance.

To predict the maximum tractive effort that the tire–ground contact can support, the normal loads on the front and rear axles have to be determined. By summing the moments of all the forces about point R (center of the tire–ground area), the normal load on the front axle W_f can be determined as

$$W_f = \frac{M_v g L_b \cos \alpha - (T_{rf} + T_{rr} + F_w h_w + M_v g h_g \sin \alpha + M h_g dV/dt)}{L} \cdot \tag{2.14}$$

Similarly, the normal load acting on the rear axle can be expressed as

$$W_r = \frac{M_v g L_a \cos \alpha - (T_{rf} + T_{rr} + R_w h_w + M_v g h_g \sin \alpha + M_v h_g dV/dt)}{L}. \tag{2.15}$$

For passenger cars, the height of the center of application of aerodynamic resistance, h_w, is assumed to be near the height of the center of gravity of the vehicle, h_g. Equations (2.14) and (2.15) can be simplified as

$$W_f = \frac{L_b}{L} M_v g \cos \alpha - \frac{h_g}{L}\left(F_w + F_g + M_v g f_r \frac{r_d}{h_g} \cos \alpha + M_v \frac{dV}{dt}\right) \tag{2.16}$$

and

$$W_r = \frac{L_a}{L} M_v g \cos \alpha + \frac{h_g}{L}\left(F_w + F_g + M_v g f_r \frac{r_d}{h_g} \cos \alpha + M_v \frac{dV}{dt}\right), \tag{2.17}$$

where r_d is the effective radius of the wheel. Referring to (2.5) and (2.13), (2.16) and (2.17) can be rewritten as

$$W_f = \frac{L_b}{L} M_v g \cos\alpha - \frac{h_g}{L}\left(F_t - F_r\left(1 - \frac{r_d}{h_g}\right)\right) \tag{2.18}$$

and

$$W_r = \frac{L_a}{L} M_v g \cos\alpha + \frac{h_g}{L}\left(F_t - F_r\left(1 - \frac{r_d}{h_g}\right)\right), \tag{2.19}$$

where $F_t = F_{tf} + F_{tr}$ is the total tractive effort of the vehicle and F_r is the total rolling resistance of the vehicle. The first term on the right-hand side of (2.18) and (2.19) is the static load on the front and rear axle when the vehicle is at rest on level ground. The second term is the dynamic component of the normal load.

The maximum tractive effort that the tire–ground contact can support (any small amount over this maximum tractive effort will cause the tire to spin on the ground) is usually described by the product of the normal load and coefficient of road adhesion μ or referred to as frictional coefficient in some literatures (more details in Section 2.4). For a front-wheel-driven vehicle,

$$F_{t\max} = \mu W_f = \mu\left[\frac{L_b}{L} M_v g \cos\alpha - \frac{h_g}{L}\left(F_{t\max} - F_r\left(1 - \frac{r_d}{h_g}\right)\right)\right] \tag{2.20}$$

and

$$F_{t\max} = \frac{\mu M_v g \cos\alpha [L_b + f_r(h_g - r_d)]/L}{1 + \mu h_g/L}, \tag{2.21}$$

where f_r is the coefficient of the rolling resistance. For a rear-wheel-driven vehicle,

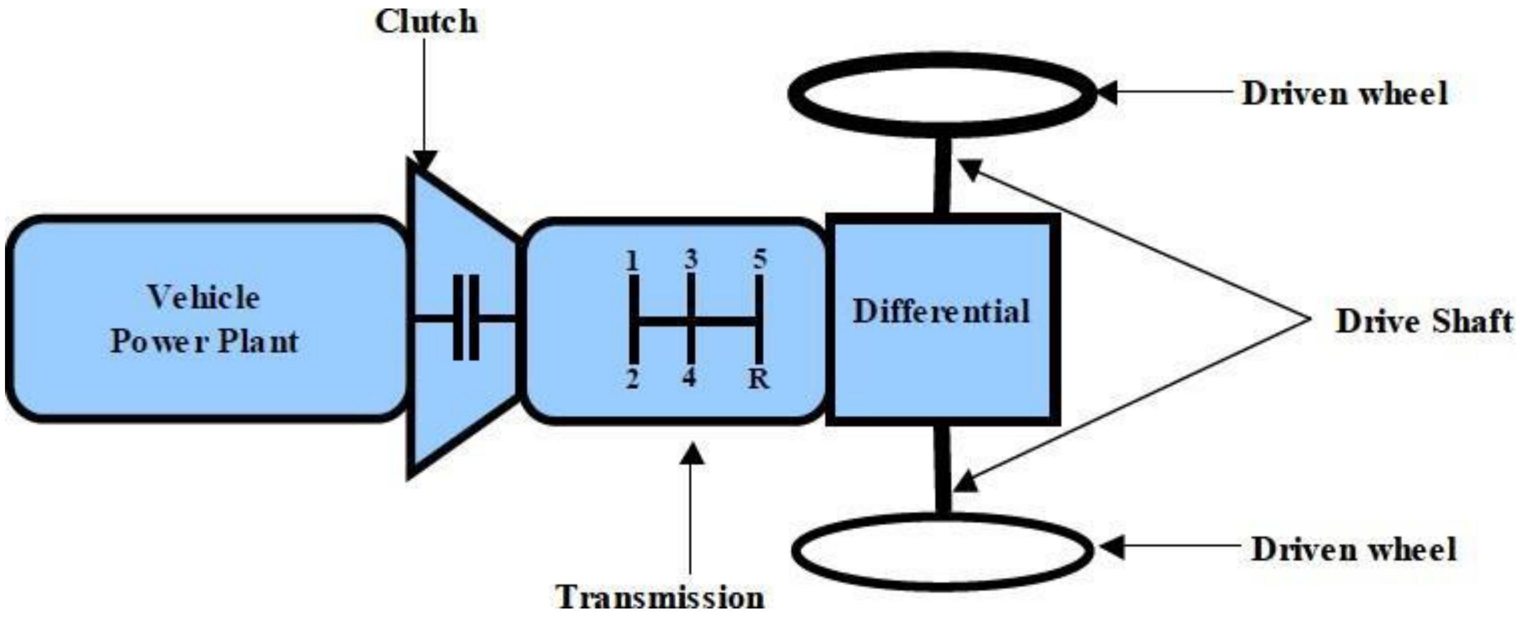
$$F_{t\max} = \mu W_r = \mu\left[\frac{L_a}{L} M_v g \cos\alpha - \frac{h_g}{L}\left(F_{t\max} - F_r\left(1 - \frac{r_d}{h_g}\right)\right)\right] \tag{2.22}$$

and

$$F_{t\max} = \frac{\mu M_v g \cos\alpha [L_a + f_r(h_g - r_d)]/L}{1 + \mu h_g/L}. \tag{2.23}$$

In vehicle operation, the maximum tractive effort on the driven wheels, transferred from the power plant through transmission, should not exceed the maximum values that are limited by the tire–ground cohesion in (2.21) and (2.23). Otherwise, the driven wheels will spin on the ground, leading to vehicle instability.

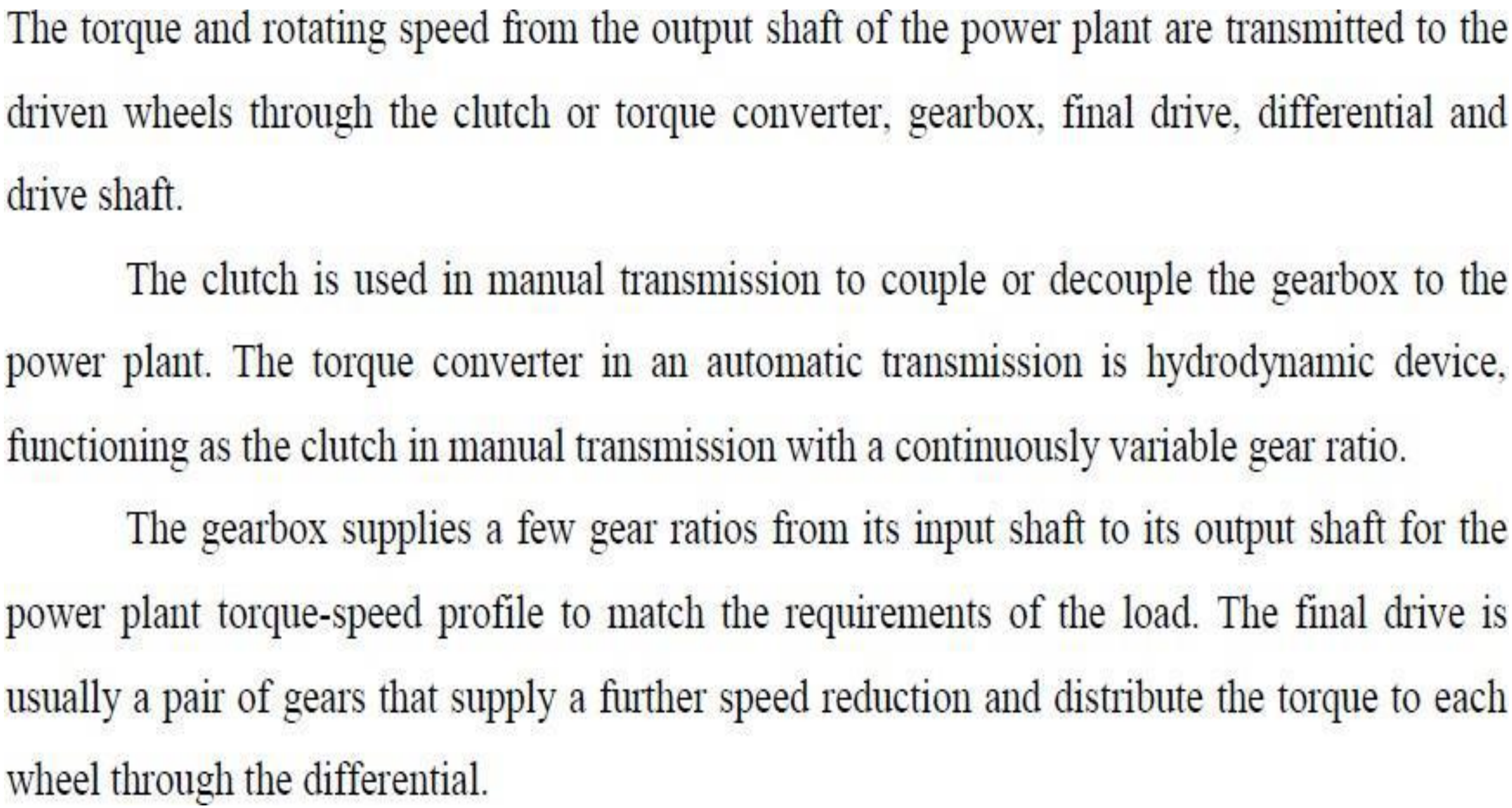
Conceptual Illustration of Automobile Power :



Drive train Configuration

An automotive drive train is shown in **Figure 1**. It consists of:

- a power plant
- a clutch in a manual transmission or a torque converter in automatic transmission
- a gear box
- final drive
- differential shaft
- driven wheels

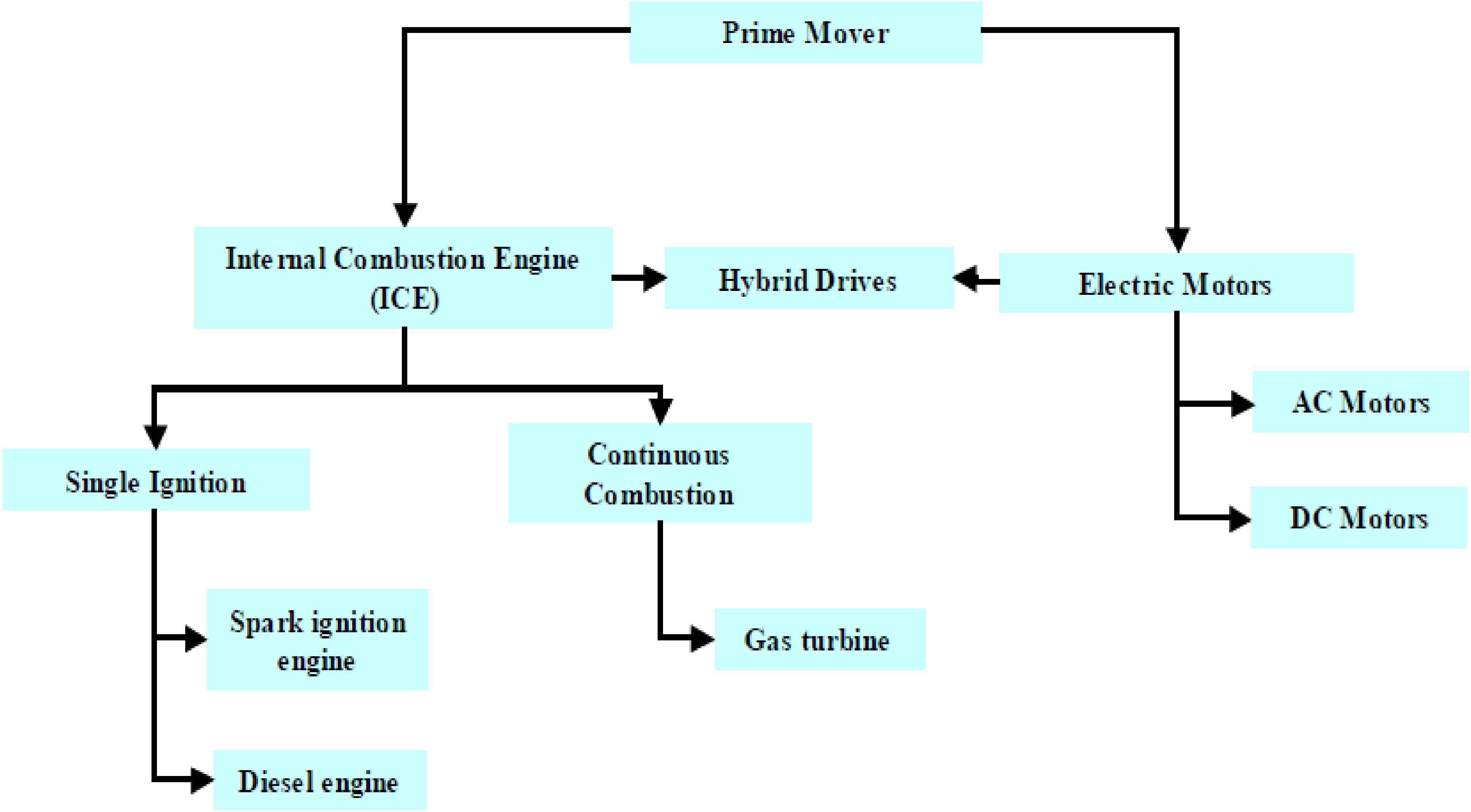


The torque and rotating speed from the output shaft of the power plant are transmitted to the driven wheels through the clutch or torque converter, gearbox, final drive, differential and drive shaft.

The clutch is used in manual transmission to couple or decouple the gearbox to the power plant. The torque converter in an automatic transmission is 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.

Classification of various Types of Vehicle Power Plant:



Prime Mover

Internal Combustion Engine (ICE)

Hybrid Drives

Electric Motors

Single Ignition

Continuous Combustion

AC Motors

DC Motors

Spark ignition engine

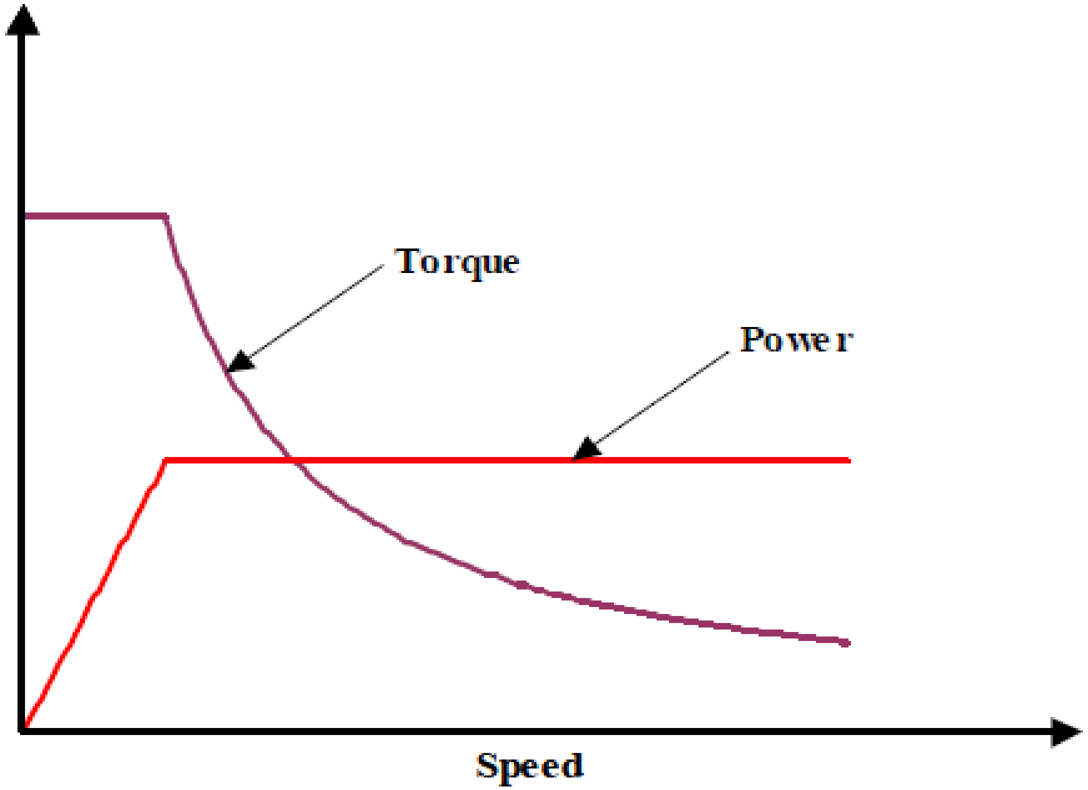
Diesel engine

Gas turbine

In selecting a suitable power plant, the following factors are considered:

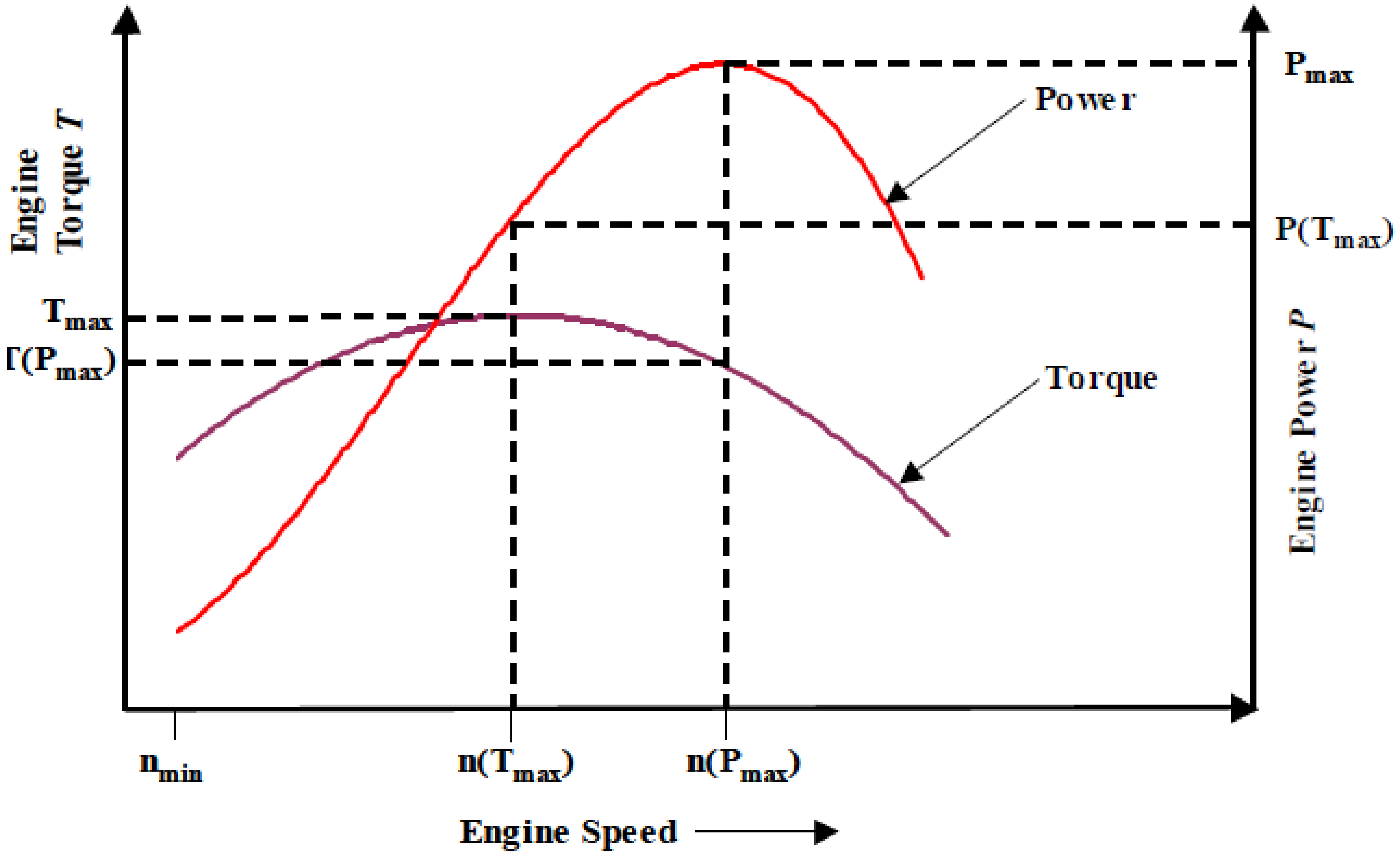
- *Operating performance*
- *Economy*
- *Environment friendliness*

Ideal performance characteristics for Vehicle Traction Power Plant:

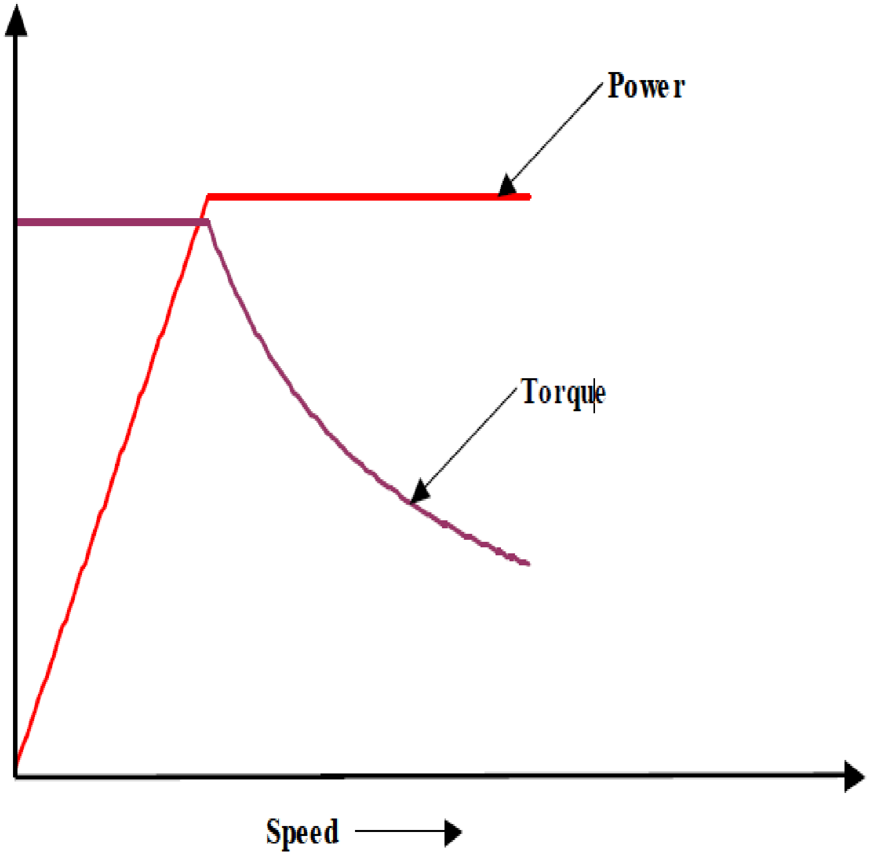


The two typical characteristic curves used to describe the engine characteristic are:

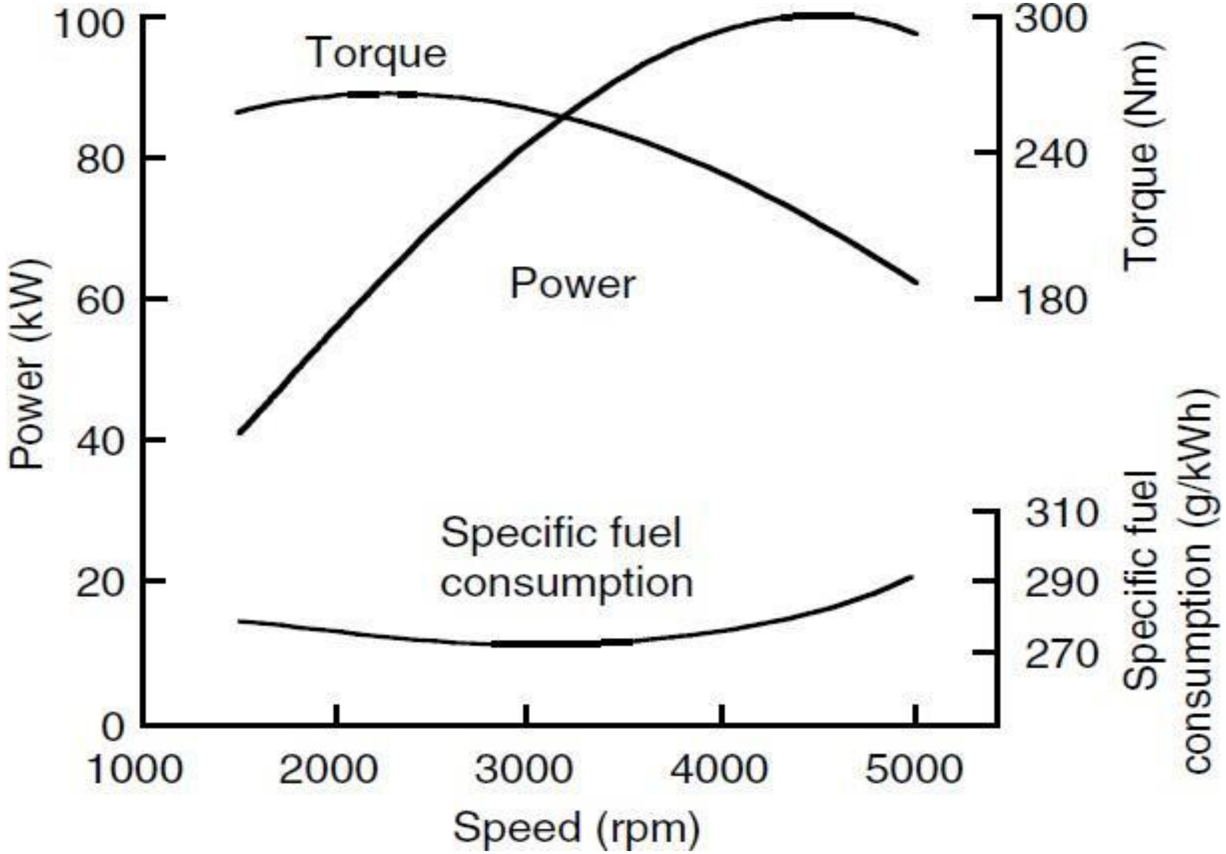
- torque vs. engine speed curve at full load (100% acceleration pedal position)
- power vs. engine speed curve at full load (100% acceleration pedal position)



Performance Characteristics :

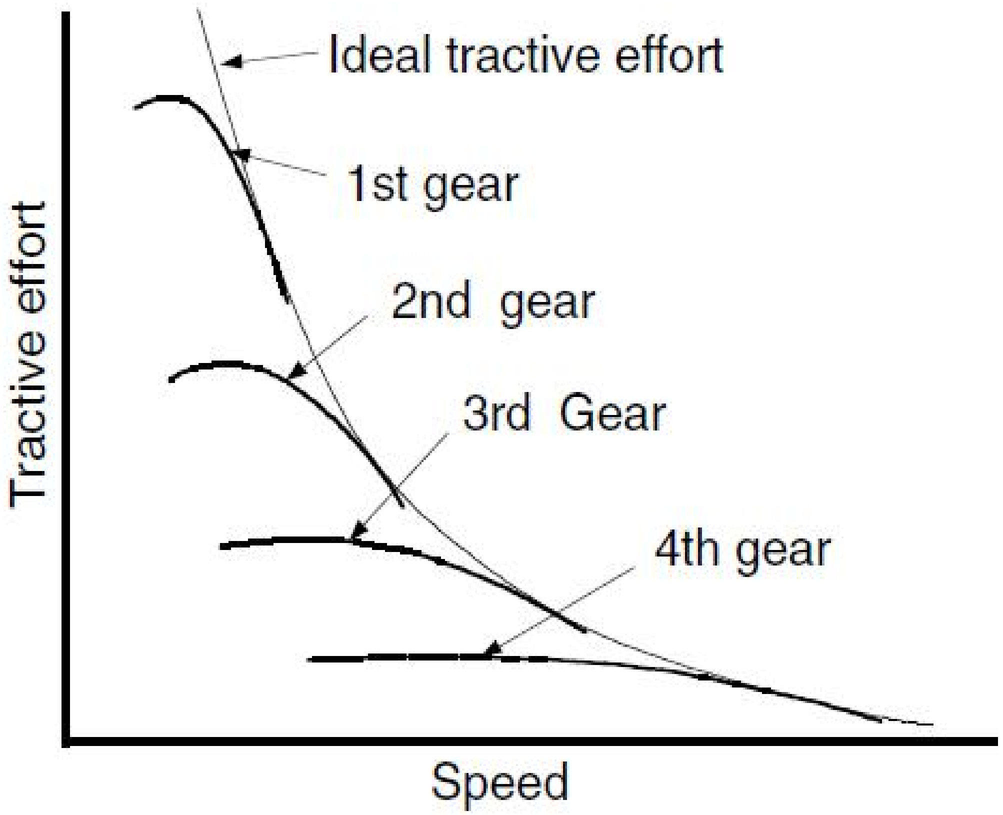


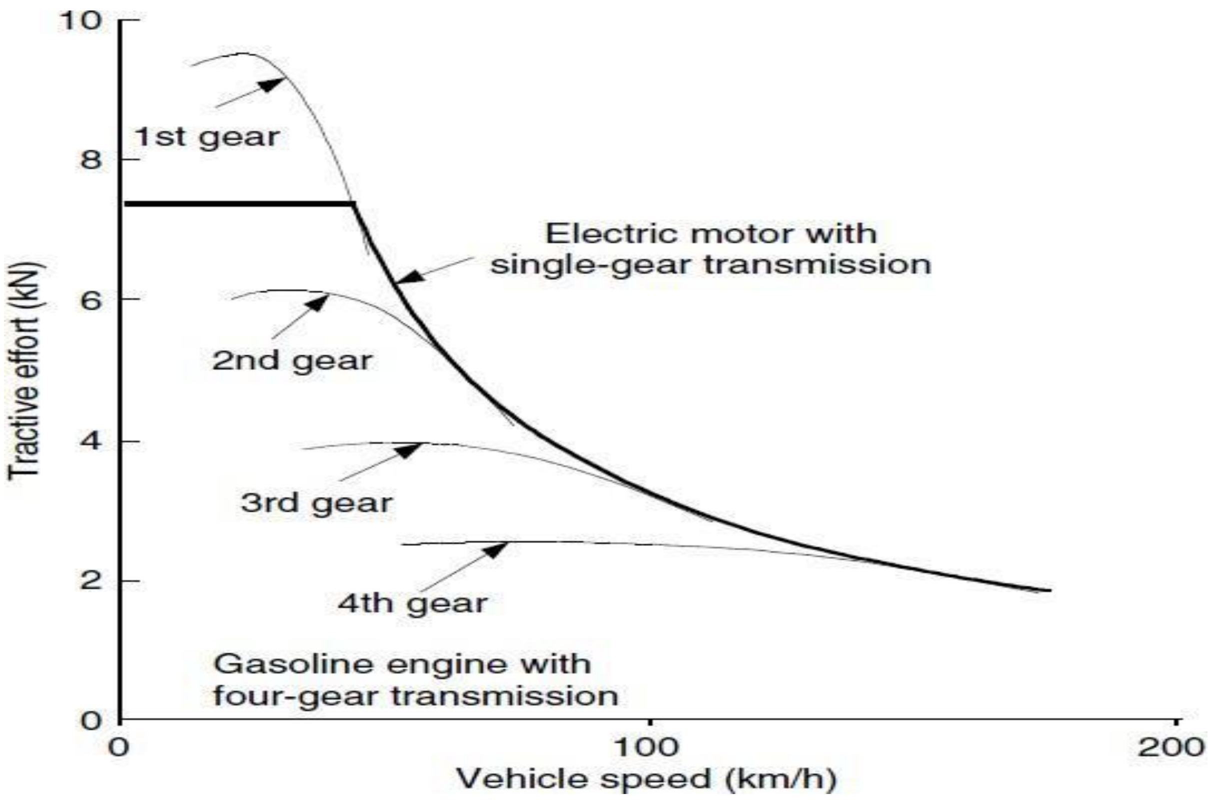
Electric Motor



Gasoline Engines

Tractive Effort Characteristics :

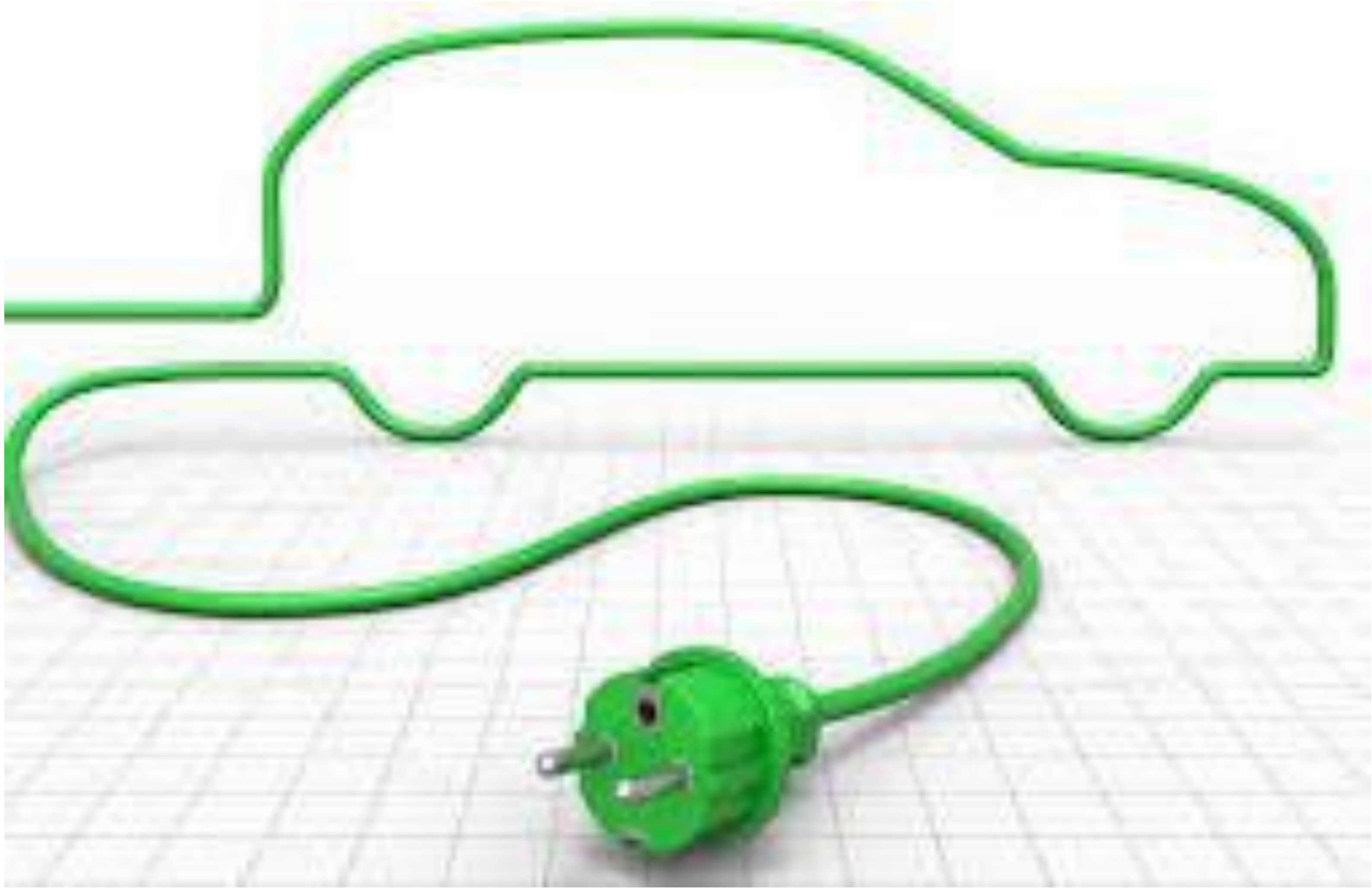




Gasoline Engines

Electric Vehicle

EE469: Electric & Hybrid Vehicles



<u>Module 2</u>

II	Hybrid Electric Drive-trains: Basic concept of hybrid traction, introduction to various hybrid drive-train topologies, power flow control in hybrid drive-train topologies, fuel efficiency analysis. Electric Drive-trains: Basic concept of electric traction, introduction to various electric drive-train topologies, power flow control in electric drive-train topologies, fuel efficiency analysis.	**7**	15%

Basic Architecture of Hybrid Drive Trains

Disadvantages of Conventional vehicles with internal combustion engines (ICE)

- Poor fuel economy
  - ❖ engine fuel efficiency characteristics are mismatched with the real operation requirements
  - ❖ dissipation of vehicle kinetic energy during braking
  - ❖ Low efficiency of hydraulic transmission in current automobiles in stop-and-go driving patterns
- Environmental pollution.

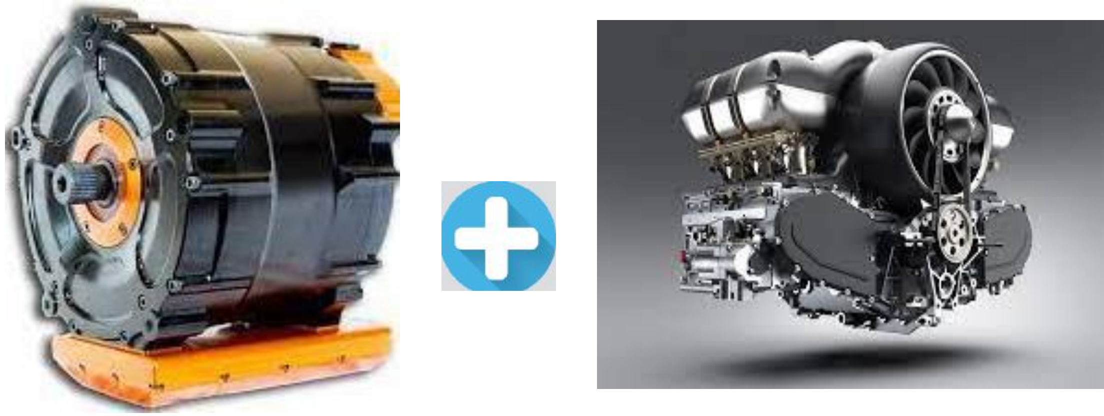
Advantages of Electric Vehicle

- Higher Energy Efficiency
- Zero Environmental pollution

Disadvantages of Electric Vehicle

- Operation range per battery charge is less competitive than ICE vehicle
- Lower Content of batteries over energy of fuels

SOLUTION : HYBRID ELECTRIC VEHICLE (HEV)



- 2 power source – primary power source & secondary source
- 1 source of power is provided by electric motor
- Other source of motive power from different technologies\
    - ❖ the gasoline ICE and battery
    - ❖ diesel ICE and battery
    - ❖ battery and FC
    - ❖ battery and capacitor
    - ❖ battery and flywheel
    - ❖ battery and battery hybrids.

Advantages of a hybrid over a conventional vehicle :

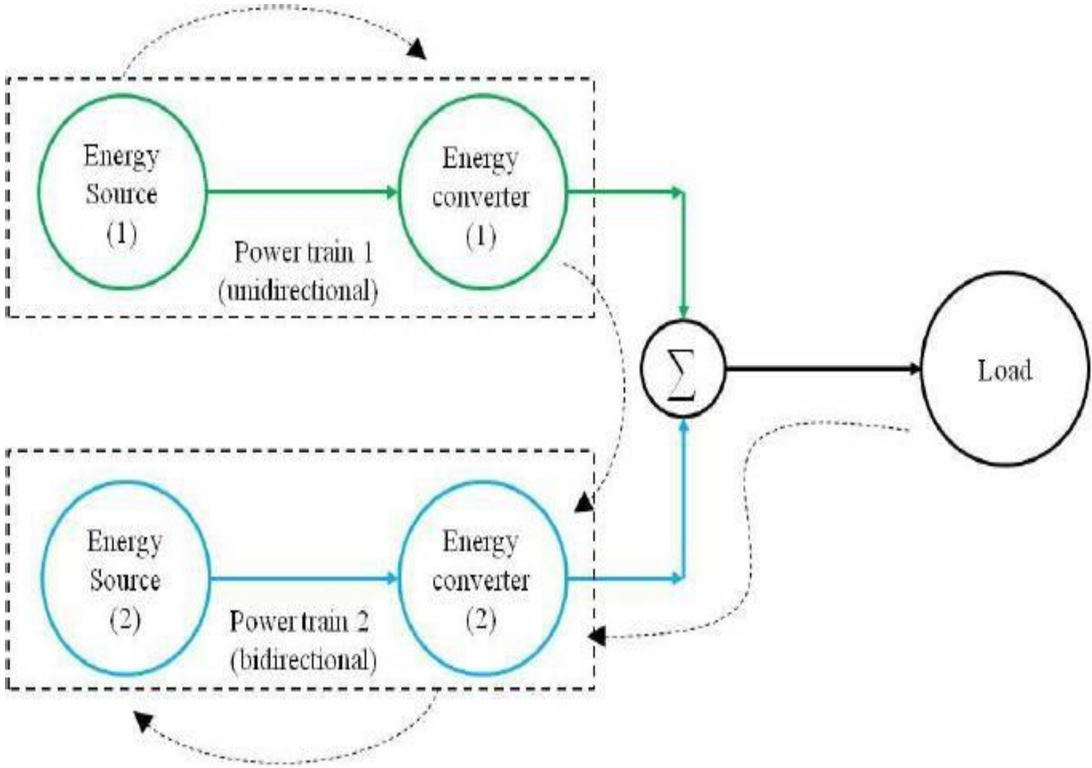
- ☐ Regenerative braking
- ☐ More efficient operation of the ICE, including reduction of idle
- ☐ Storage device can take up a part of the load, the HEV’s ICE can be down sized

Disadvantages of a hybrid vehicle :

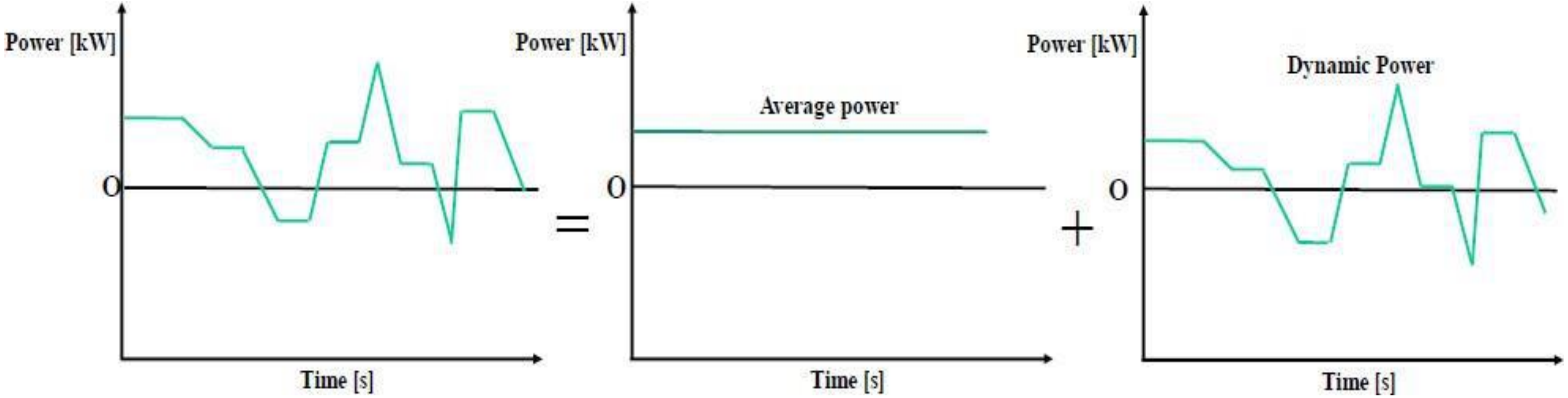
- Potential for higher weight
- Electrical losses

Hybrid Electric Drive Trains

- Hybrid vehicles have 2 power sources -2 power trains
- Possible ways of combining the power flow to meet the driving requirements are:
    - i. Powertrain 1 alone delivers power
    - ii. Powertrain 2 alone delivers power
    - iii. Both powertrain 1 and 2 deliver power to load at the same time
    - iv. Powertrain 2 obtains power from load (regenerative braking)
    - v. Powertrain 2 obtains power from Powertrain 1
    - vi. Powertrain 2 obtains power from Powertrain 1 and load at the same time
    - vii. Powertrain 1 delivers power simultaneously to load and to Powertrain 2
    - viii. Powertrain 1 delivers to Powertrain 2 and Powertrain 2 delivers to load
    - ix. Powertrain 1 delivers power to load and load delivers power to Powertrain 2



The power requirement for a typical driving scenario is shown in **Figure below**



The load power can be decomposed into two parts:

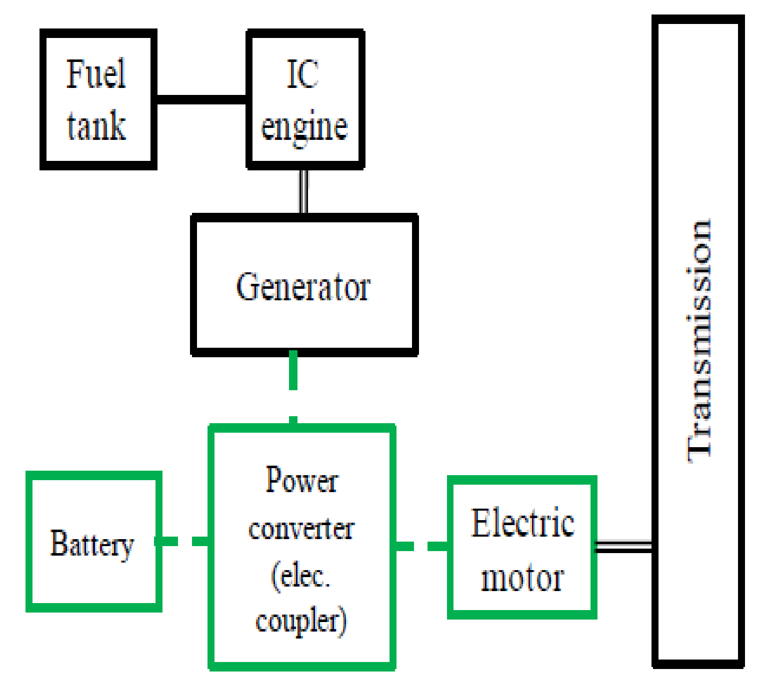
i.steady power, i.e. the power with a constant value
ii.dynamic power, i.e. the power whose average value is zero

In HEV one powertrain favors steady state operation, such as an ICE or fuel cell. Electric motors are used to meet the dynamic power demand. This hybrid drivetrain concept can be implemented by different configurations as follows:

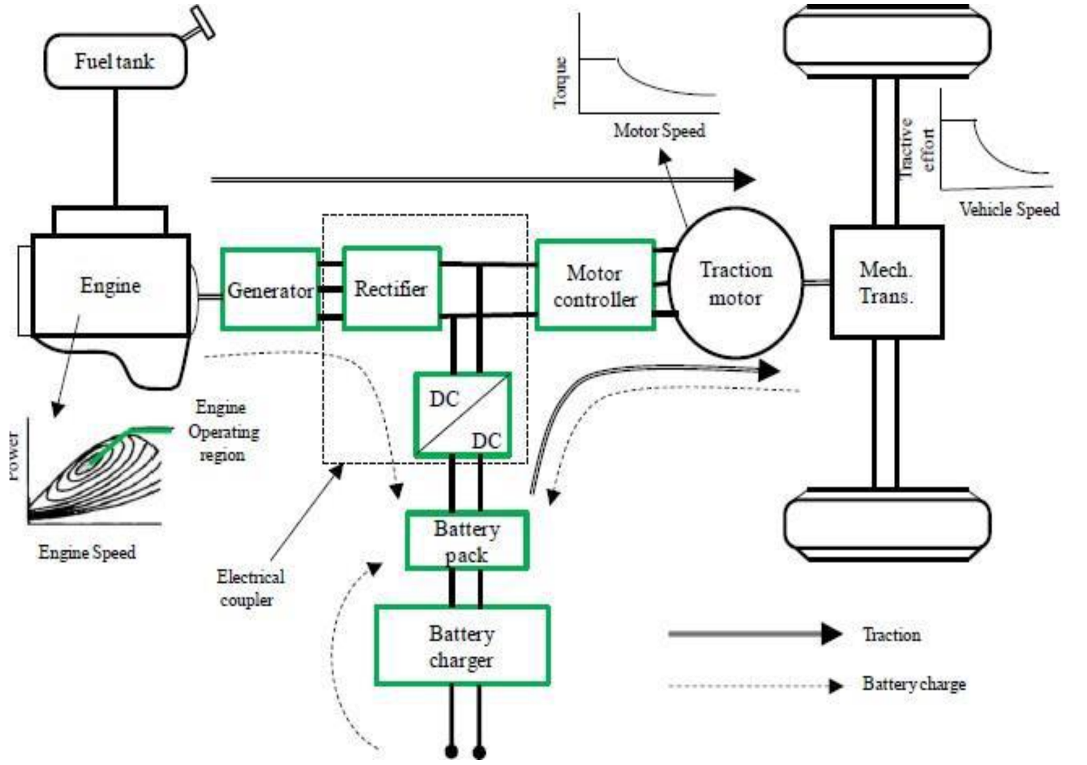
1. **Series configuration**
2. **Parallel configuration**
3. **Series-parallel configuration**
4. **Complex configuration**

1. Series Hybrid System configuration

The mechanical output is first converted into electricity using a generator. The converted electricity either charges the battery or can bypass the battery to propel the wheels via the motor and mechanical transmission.



Functional block diagrams of series hybrid configuration



Detailed configuration of series hybrid vehicle

1. Series Hybrid System configuration

Advantages of series hybrid drivetrains

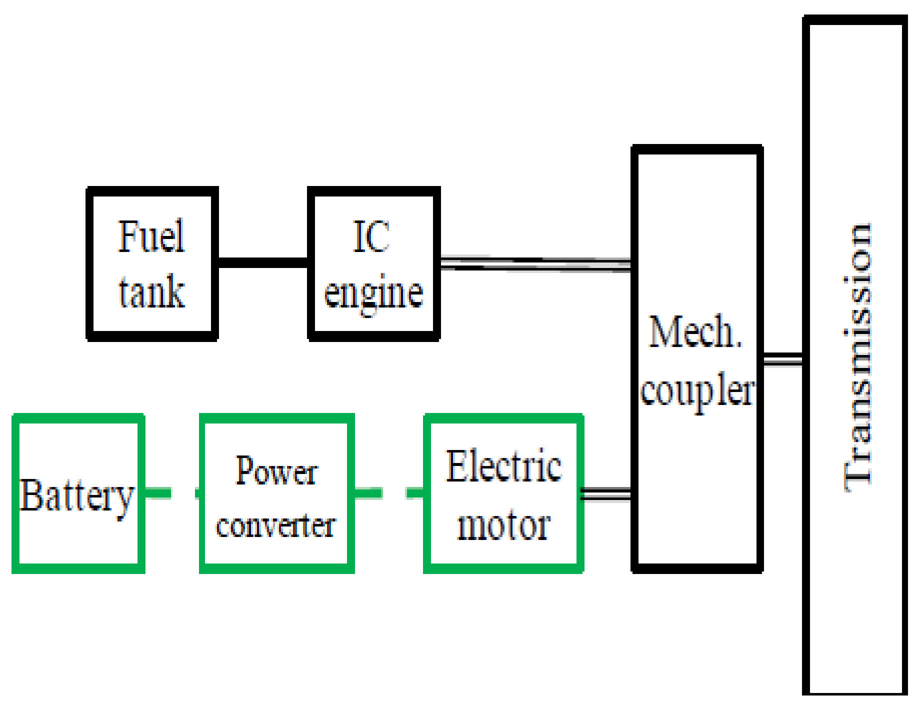
- Mechanical decoupling between the ICE and driven wheels allows the IC engine operating at its very narrow optimal region
- Nearly ideal torque-speed characteristics of electric motor make multi gear transmission unnecessary.

Disadvantages of series hybrid drivetrains

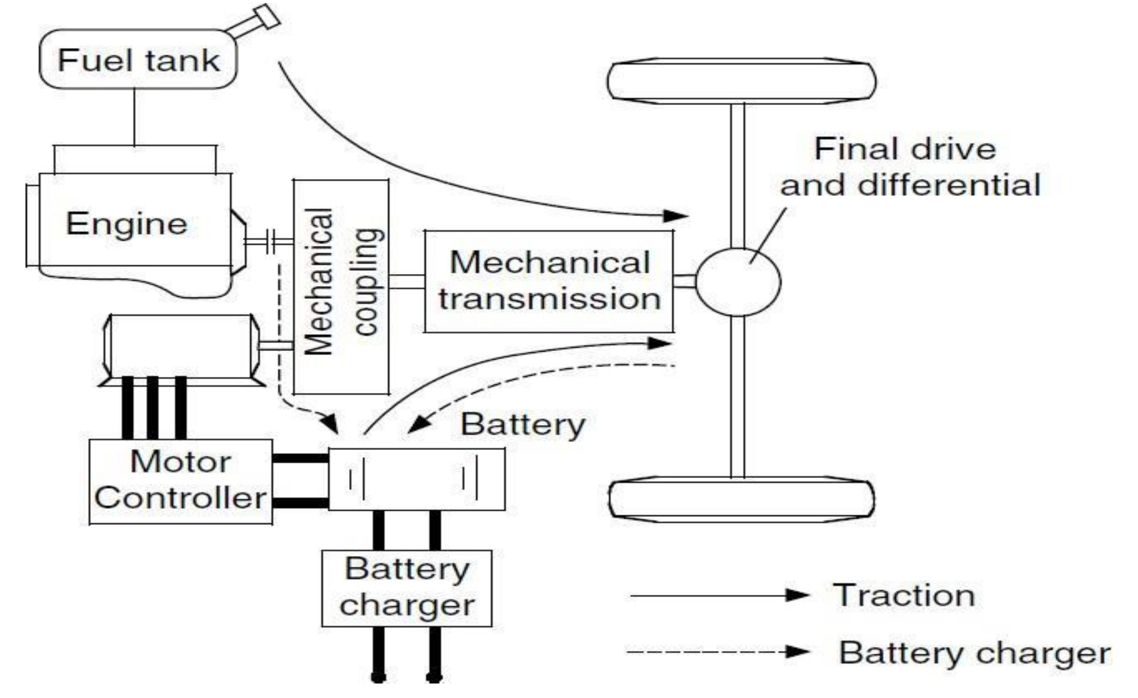
- The energy is converted twice (mechanical to electrical and then to mechanical) and this reduces the overall efficiency.
- Two electric machines are needed and a big traction motor is required because it is the only torque source of the driven wheels.

2. Parallel Hybrid System configuration

- ICE and electric motor (EM) to deliver power to drive the wheels.
- EM can be used as a generator to charge the battery by regenerative braking or absorbing power from the ICE when its output is greater than that required to drive the wheels.



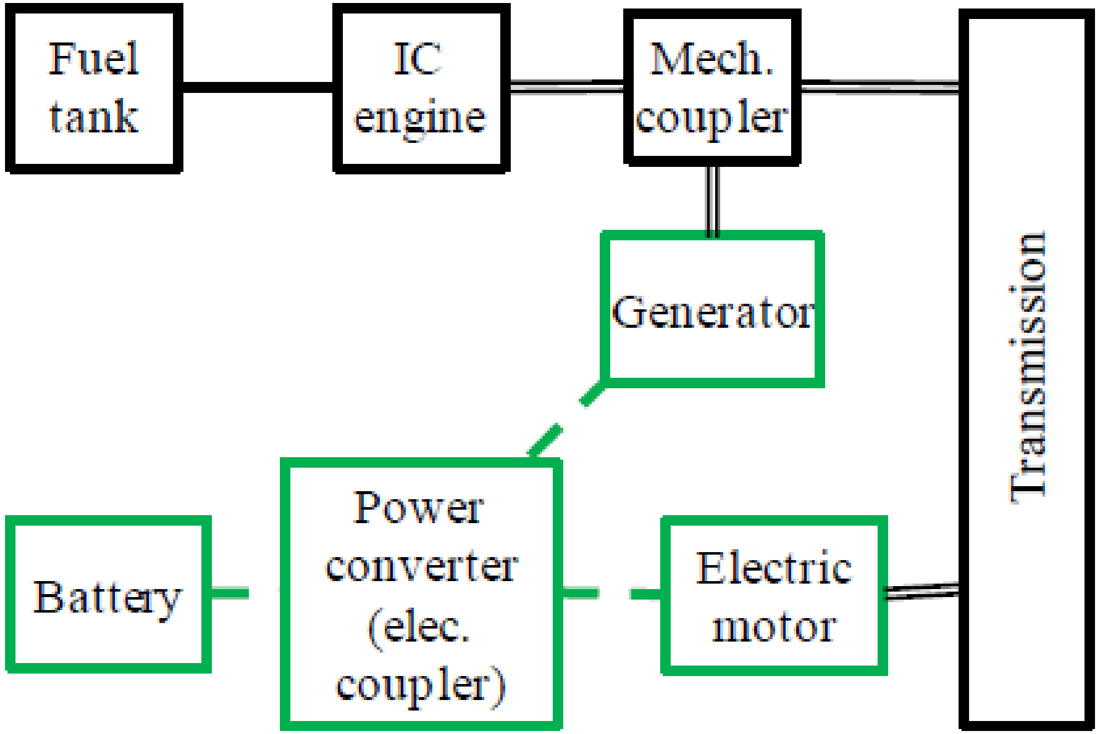
Functional block diagrams of parallel hybrid configuration



Configuration of a parallel hybrid electric drive train

3. Series-Parallel hybrid system configuration

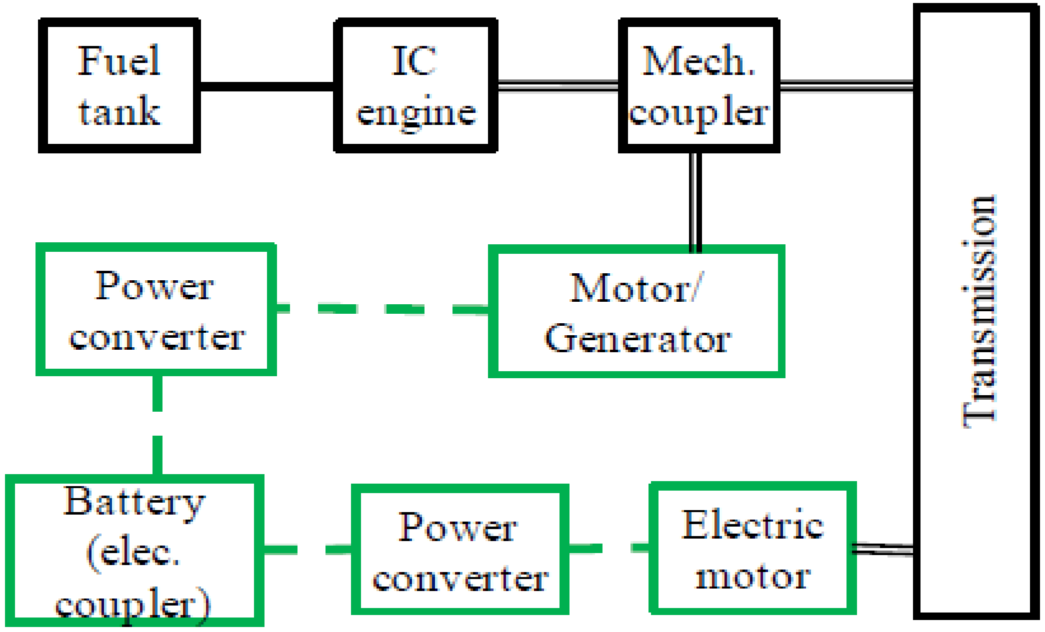
- Incorporates the features of both the series and parallel HEVs.
- It needs an additional electric machine and a planetary gear unit making the control complex.



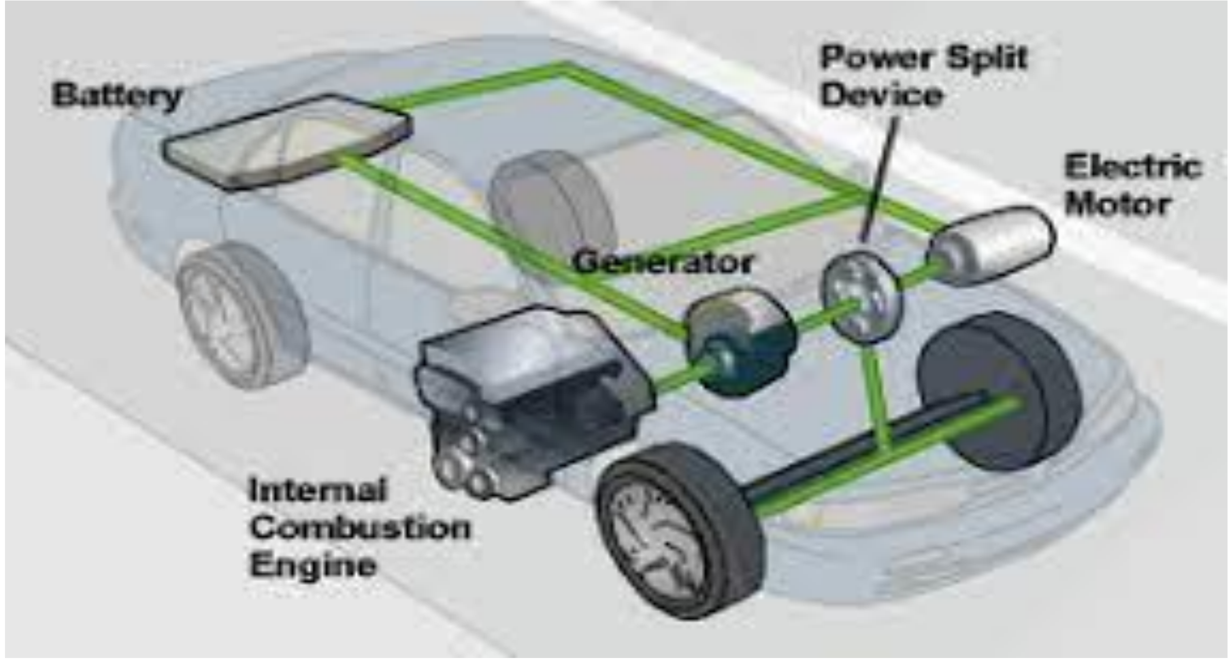
Functional block diagrams of Series-Parallel hybrid configuration

4. Complex hybrid system configuration

- The complex hybrid is similar to the series-parallel hybrid since the generator and electric motor is both electric machines.
- The key difference is due to the bi-directional power flow of the electric motor in complex hybrid and the unidirectional power flow of the generator in the series- parallel hybrid.
- Disadvantage : higher complexity.

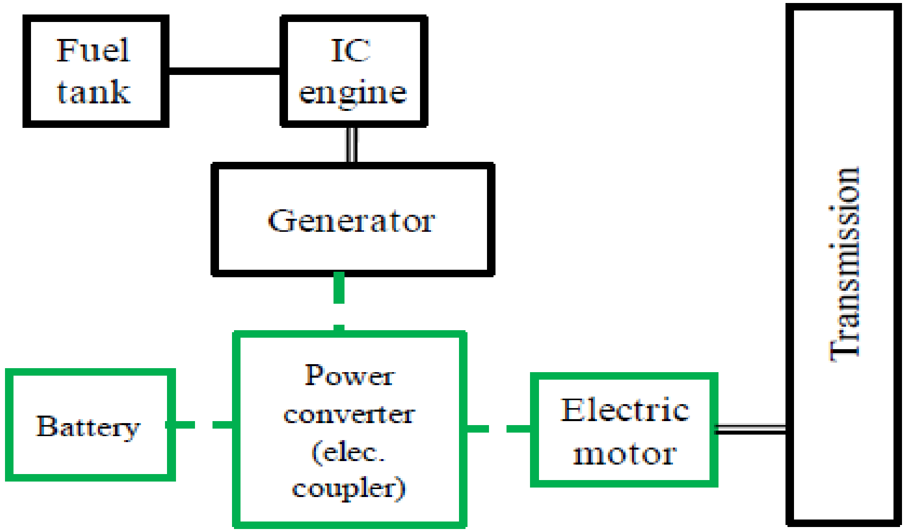


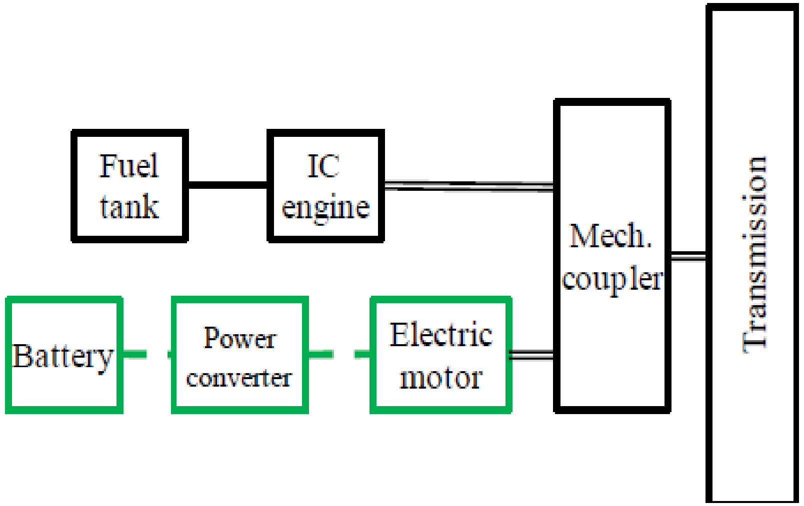
Functional block diagrams of complex hybrid configuration

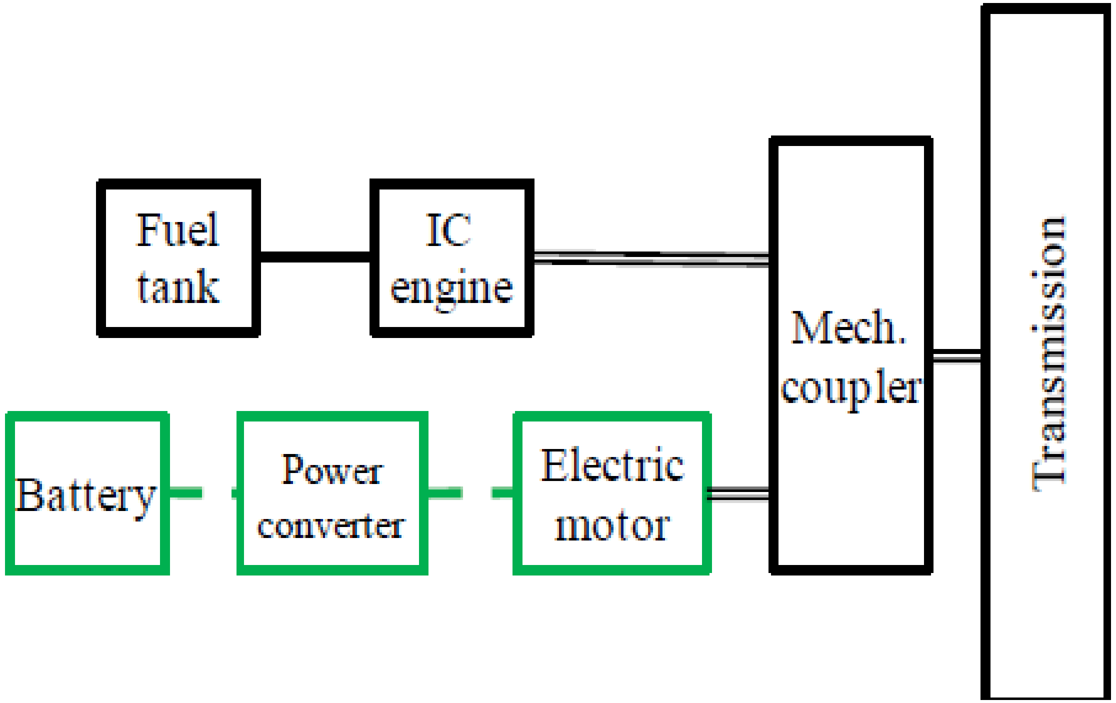

Battery
Power Split Device
Electric Motor
Generator
Internal Combustion Engine

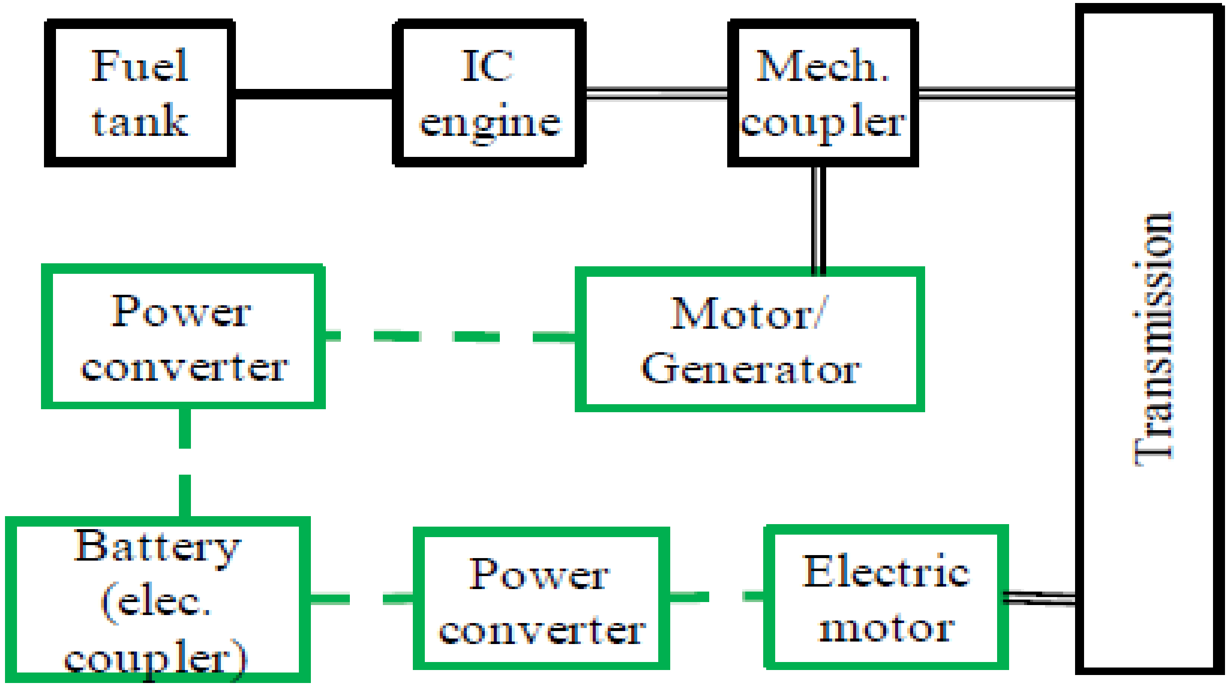
Hybrid drivetrain configurations:

- *Series configuration*
- *Parallel configuration*
- *Series-parallel configuration*
- *Complex configuration*









Power flow control in hybrid drive train topology :

AIM :

1. Maximum fuel efficiency
2. Minimum emissions
3. Minimum system costs
4. Good driving performance

Considerations :

- ***Optimal ICE operating point :*** The optimal operating point on the torque-speed plane of the ICE can be based on maximization of fuel economy, the minimization of emissions or a compromise between fuel economy and emissions.

- ***Optimal ICE operating line:*** In case the ICE needs to deliver different power demands, the corresponding optimal operating points constitute an optimal operating line.

- ***Safe battery voltage: B***attery voltage should not exceed the maximum voltage limit nor should it fall below the minimum voltage limit.

1 Series Hybrid Power Flow Control

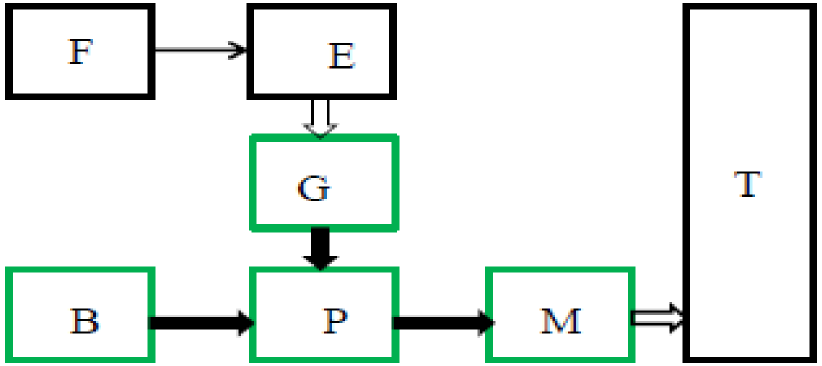


Figure 1a: Mode 1, normal driving or acceleration

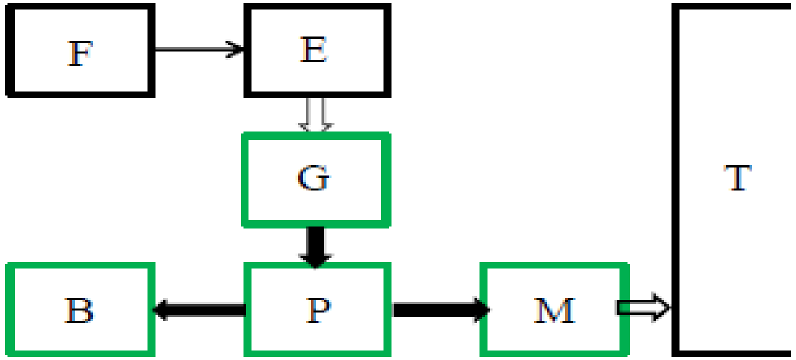


Figure 1b: Mode 2, light load

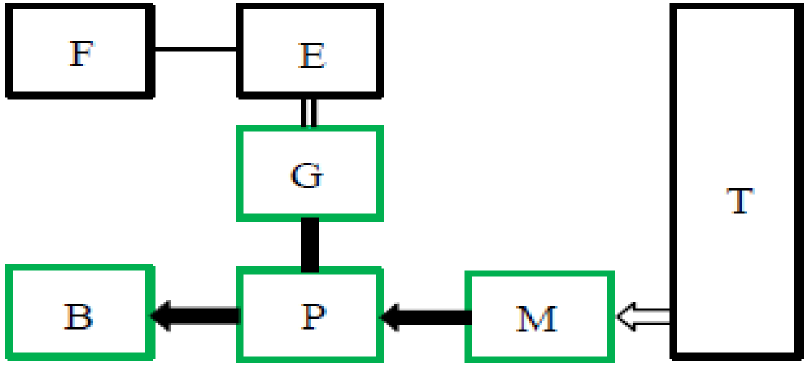


Figure 1c: Mode 3, braking or deceleration [1]

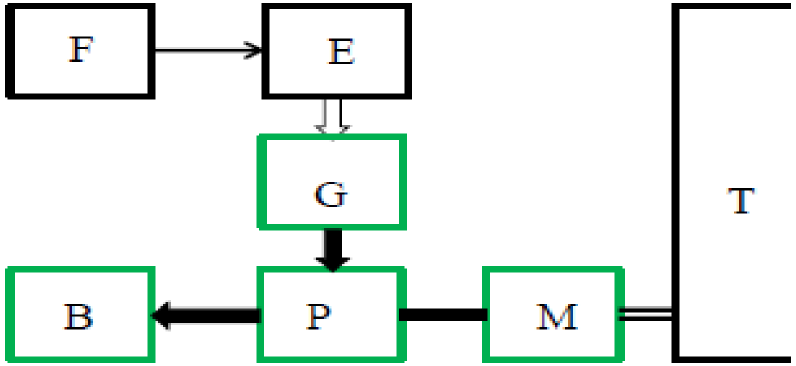


Figure 1d: Mode 4, vehicle at stop

B:Battery
E: ICE
F: Fuel tank

G: Generator
M: Motor
P: Power Converter

━ Electrical link
— Hydraulic link
═ Mechanical link

T: Transmission (including brakes, clutches and gears)

- **Mode 1: S**tartup, ICE & battery deliver energy to the Power converter

- **Mode 2:** Light load, ICE output greater than required drive power. Fraction of the generated energy is used to charge the battery.

- **Mode 3: B**raking, motor acts as a generator, converts the kinetic energy into electricity and is used to charge the battery.

- **Mode 4:** The battery can be charged by the ICE via the generator even when the vehicle comes to a complete stop

2. Power Flow Control in Parallel Hybrid

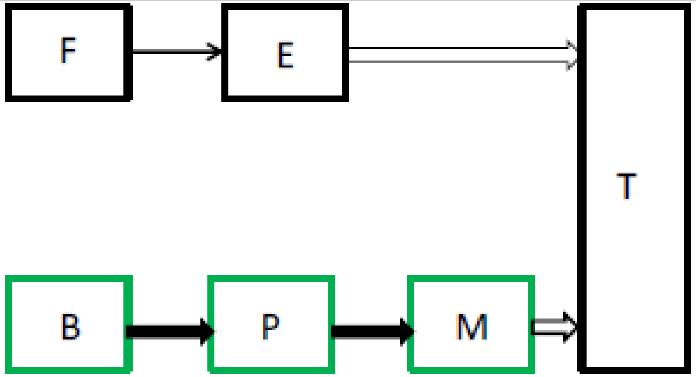


Figure 2a: Mode 1, start up

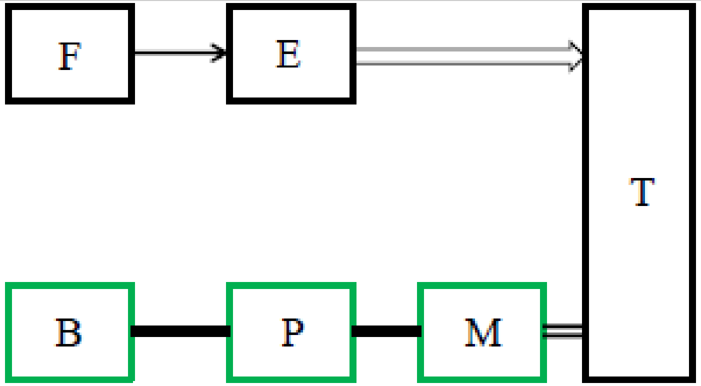


Figure 2b: Mode 2, normal driving

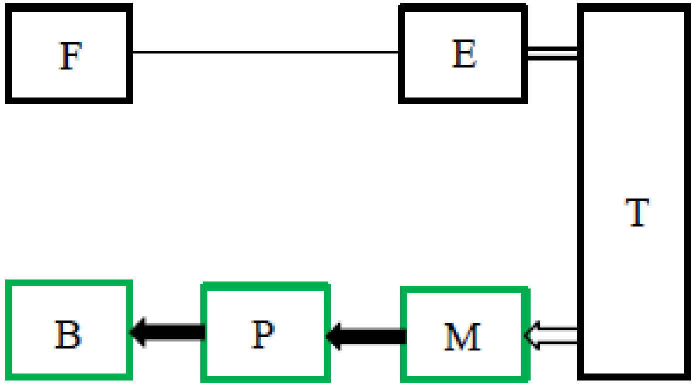


Figure 2c: Mode 3, braking or deceleration [1]

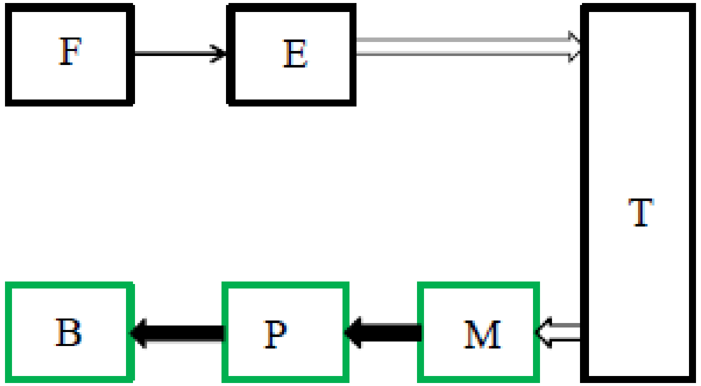


Figure 2d: Mode 4, light load

- **Mode 1: S**tart up: both the ICE and the EM share power to vehicle. Relative distribution between the ICE and electric motor is 80-20%.
- **Mode 2: N**ormal driving: required power is supplied by the ICE only and the EM remains in off mode.
- **Mode 3: B**raking: the EM acts as a generator to charge the battery.
- **Mode 4: L**ight load condition : traction power is delivered by the ICE and ICE also charges the battery.

3. Power Flow Control Series-Parallel Hybrid

3.1. Operating modes of **ICE dominated** system:

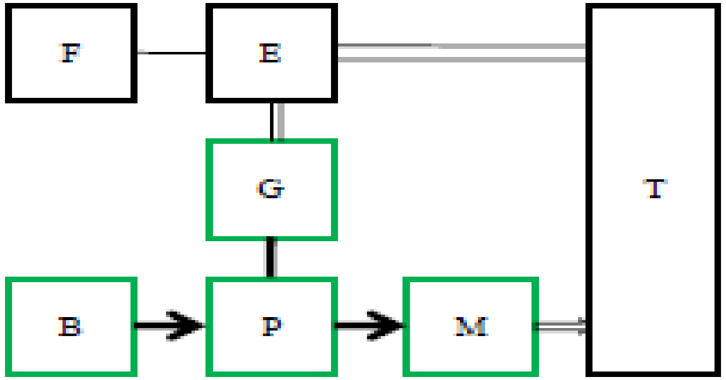


Figure 3a: Mode 1, start up [1]

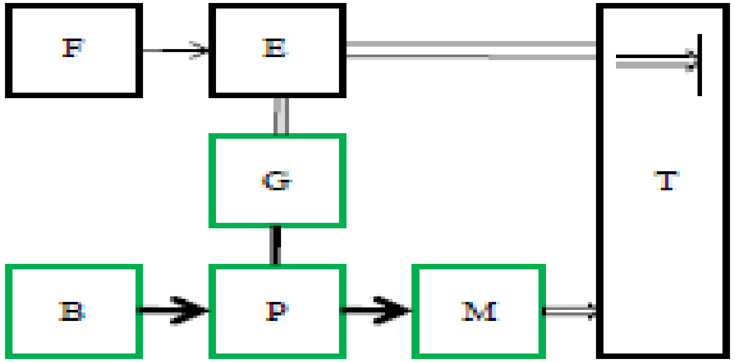


Figure 3b: Mode 2, acceleration [1]

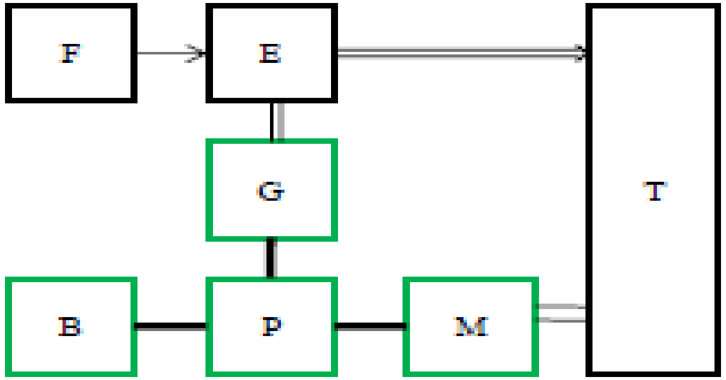


Figure 3c: Mode 3, normal drive [1]

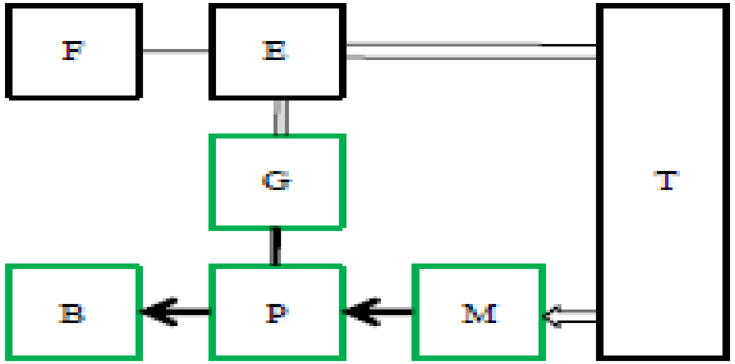


Figure 3d: Mode 4, braking or deceleration [1]

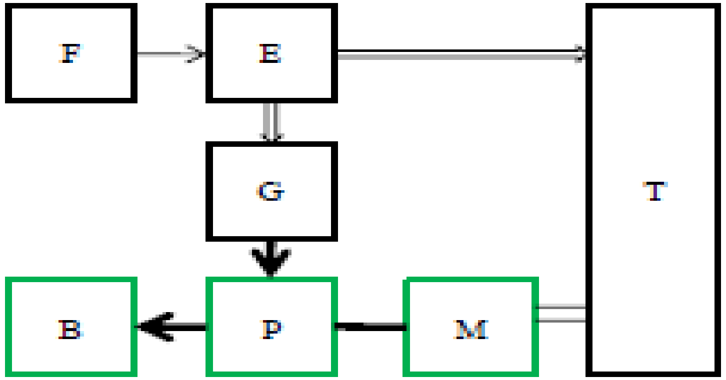


Figure 3e: Mode 5, battery charging during dri

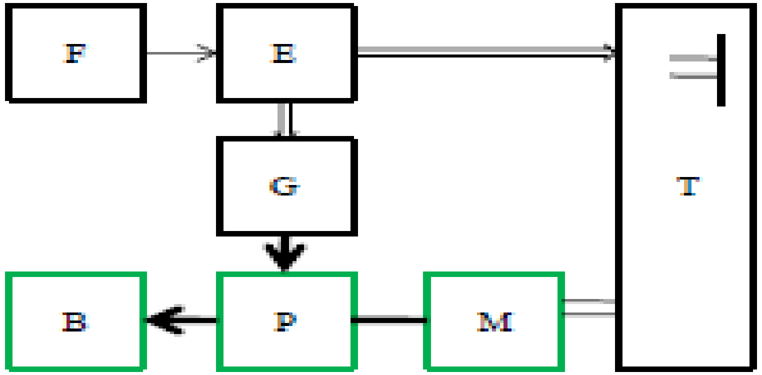


Figure 3f: Mode 6, battery charging during standstill

- **Mode 1:** **S**tartup: battery provides power to vehicle and ICE remains in off mode.
- **Mode 2:** full throttle acceleration , ICE and the EM share the required power.
- **Mode 3:** **N**ormal driving : required power is provided by ICE only & EM remains in the off state.
- **Mode 4:** **N**ormal braking : EM acts as a generator to charge the battery.
- **Mode 5:** To charge the battery during driving : ICE delivers the required power & charges the battery - EM acts as a generator.
- **Mode 6:** **At** standstill : ICE can deliver power to charge the battery via the EM

3. Power Flow Control Series-Parallel Hybrid *3.2 Operating modes of **EM dominated** system*

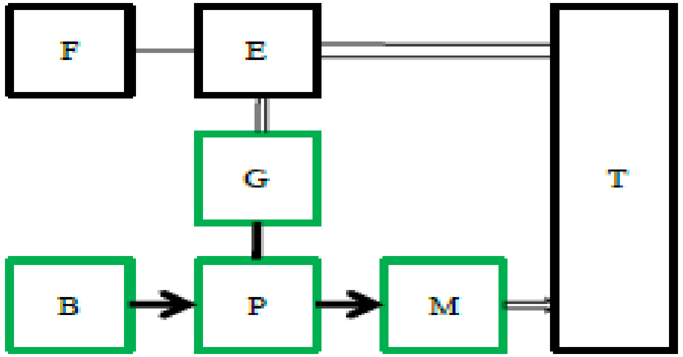


Figure 4a: Mode 1, start up [1]

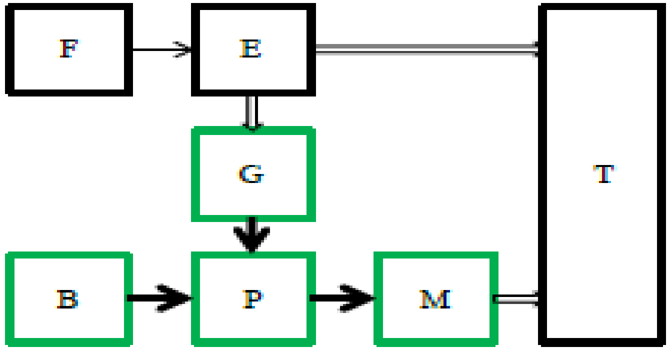


Figure 4b: Mode 2, acceleration [1]

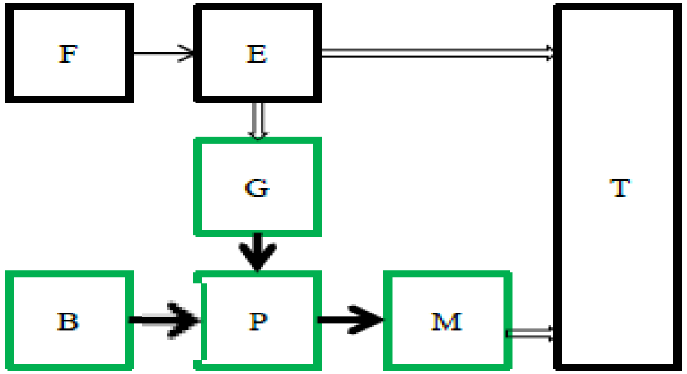


Figure4c: Mode 3, normal drive [1]

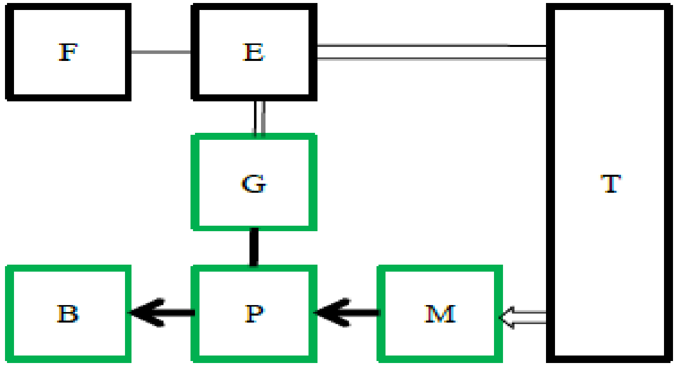


Figure 4d: Mode 4, braking or deceleration [1]

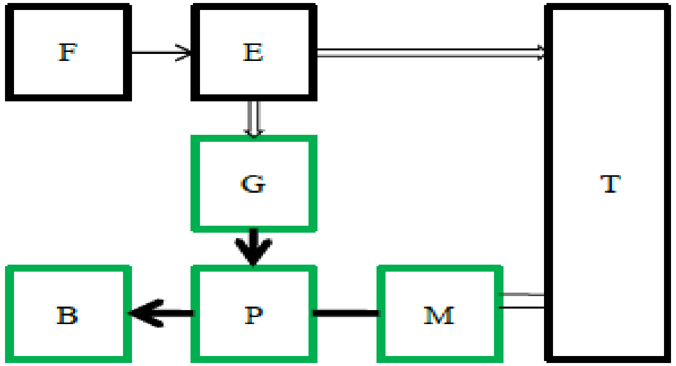


Figure 4e: Mode 5, battery charging during driving [1]

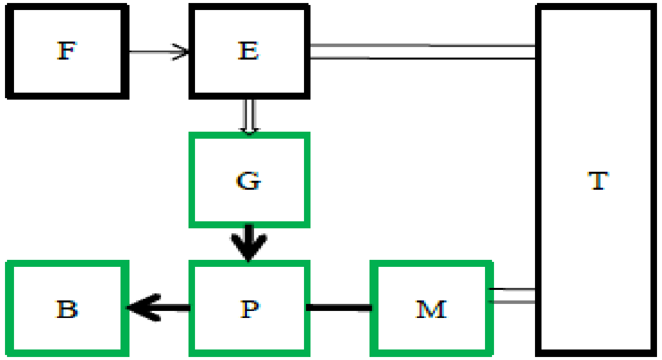


Figure 4f: Mode 6, battery charging during standstill

- **Mode 1:** Startup : EM provides power & ICE remains in the off state.
- **Mode 2:** Full throttle ICE & EM provide power.
- **Mode 3:** Normal driving ICE & EM provide power.
- **Mode 4:** Braking : EM acts as a generator to charge the battery.
- **Mode 5:** To charge the battery during driving : ICE delivers the required power and also charges the battery. EM acts as a generator.
- **Mode 6: At** standstill: ICE can deliver power to charge the battery via the EM

4. Power Flow Control Complex Hybrid Control

The complex hybrid vehicle configurations are of two types:

1. Front hybrid rear electric
2. Front electric and rear hybrid

- **Mode 1:** **S**tartup : required power is delivered by the EMs and the engine is in off mode.
- **Mode 2:** **F**ull throttle acceleration : ICE and the front wheel EM deliver the power to the front wheel and the second EM delivers power to the rear wheel.
- **Mode 3:** **N**ormal driving : ICE delivers power to propel the front wheel and to drive the first EM as a generator to charge the battery.

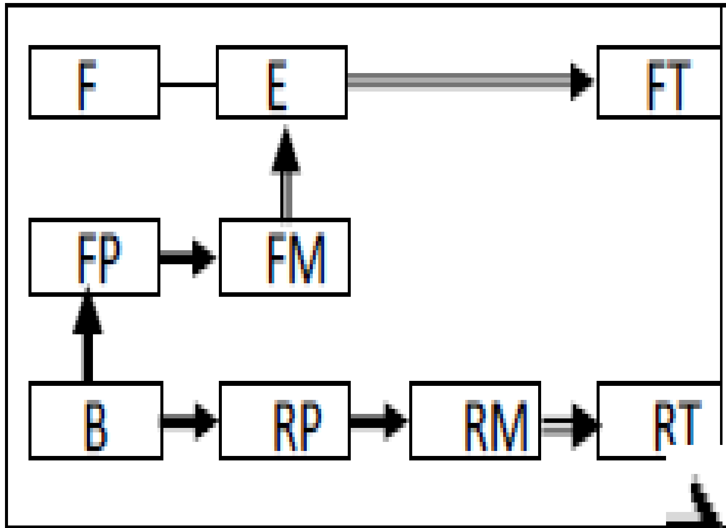


Figure 5a: Mode 1, startup

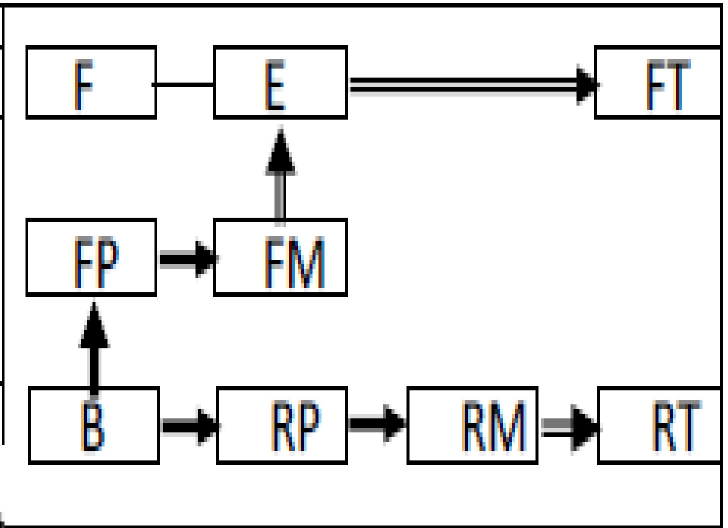


Figure 5b: Mode 2, full throttle acceleration

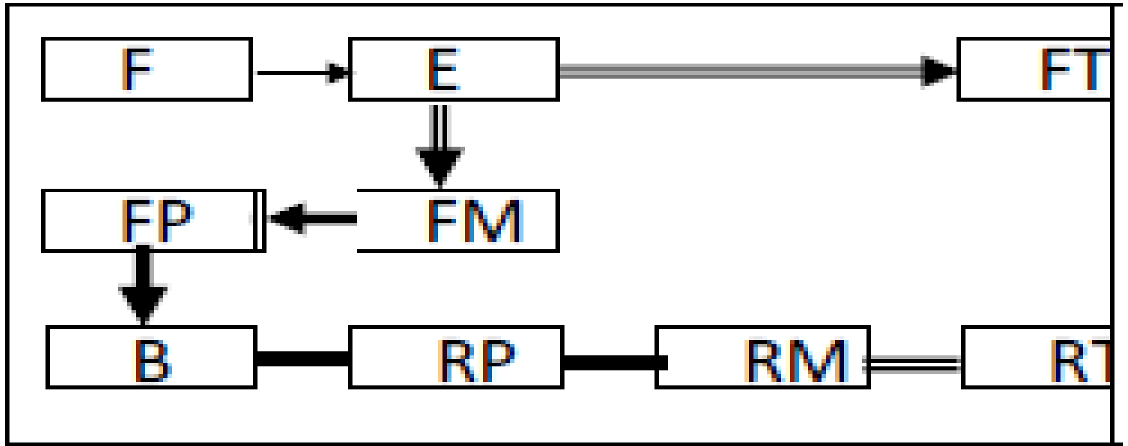


Figure 5c: Mode 3, vehicle propel and battery charging

B:Battery FM: Front motor FP: Front power converter FT: Front axel transmission E: ICE F: Fuel tank RM: Rear motor RP: Rear power converter RT: Rear axle transmission [1]

▬ Electrical link
— Hydraulic link

- **Mode 4:** Light load, first EM delivers required power to the front wheel. The second EM and the ICE are in off sate.

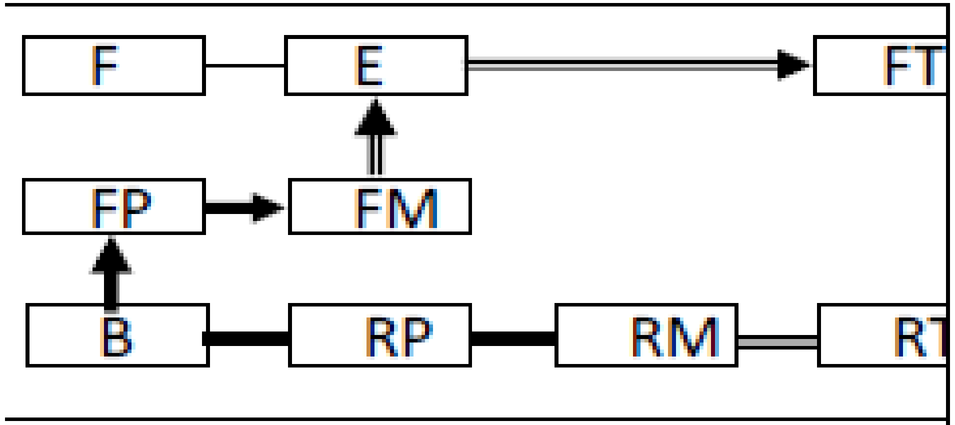


Figure 5d: Mode 4 light load

- **Mode 5:** Braking: front and rear wheel EMs act as generators to charge the battery.

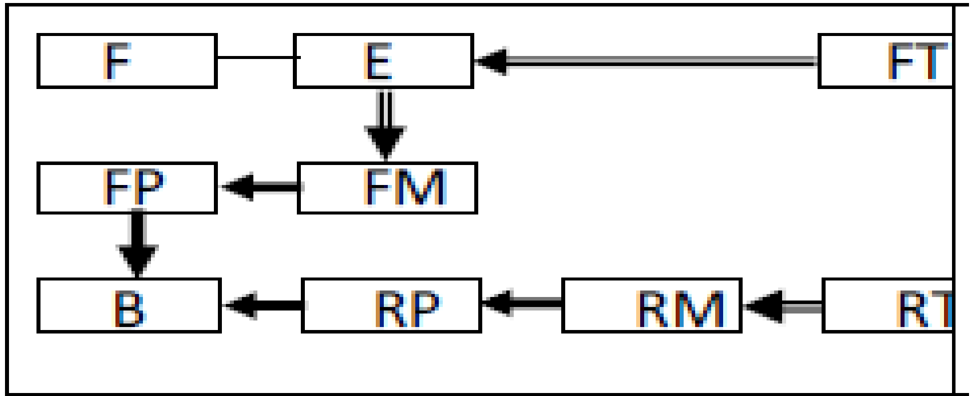


Figure 5e: Mode 5, braking or decelration

- **Mode 6:** Unique mode- ***Axial balancing*** - In this mode if the front wheel slips, the front EM works as a generator to absorb the change of ICE power. Through the battery, this power difference is then used to drive the rear wheels to achieve the axle balancing.

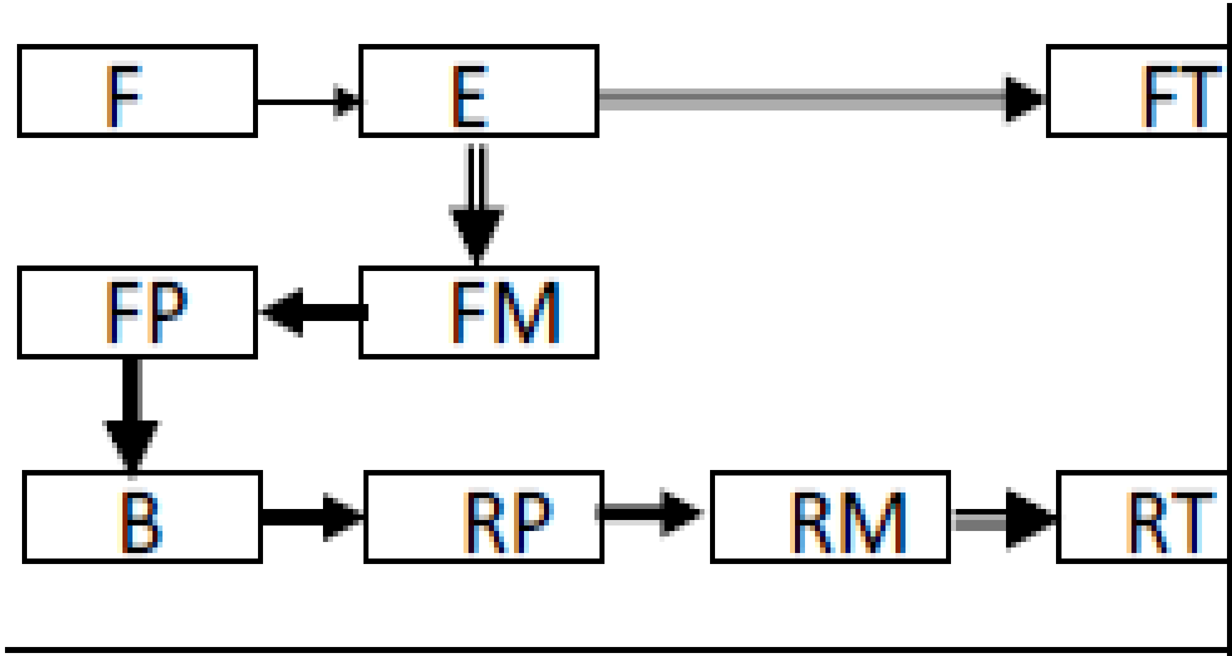


Figure 5f: Mode 1, axil balancing

B:Battery FM: Front motor FP: Front power converter FT: Front axel transmission E: ICE F: Fuel tank
RM: Rear motor RP: Rear power converter RT: Rear axle transmission [1]

━ Electrical link
─ Hydraulic link

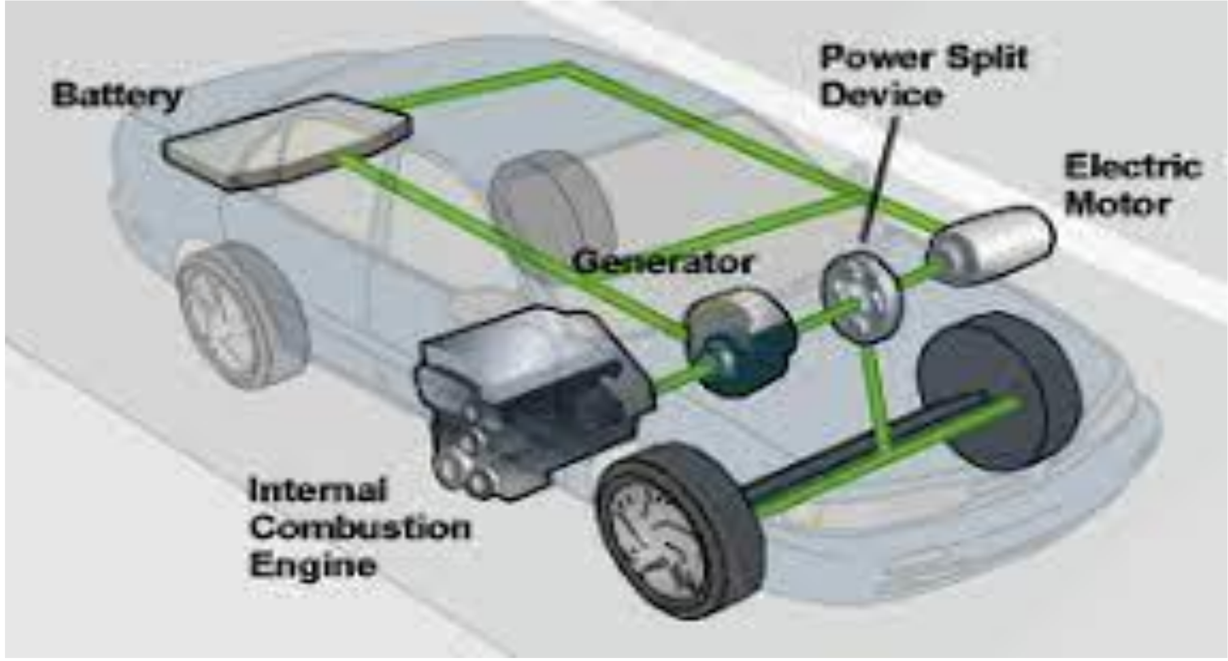
Architecture of Electric Drive Trains

Electric Vehicle (EV) Configurations Compared to HEV, the configuration of EV is flexible. The reasons for this flexibility are:

1. The energy flow in EV is mainly via flexible electrical wires rather than bolted flanges or rigid shafts. Hence, distributed subsystems in the EV are really achievable.
2. The EVs allow different propulsion arrangements such as independent four wheels and in wheel drives.

The EV has three major subsystems:

- ***Electric propulsion***
- ***Energy source***
- ***Auxiliary system***



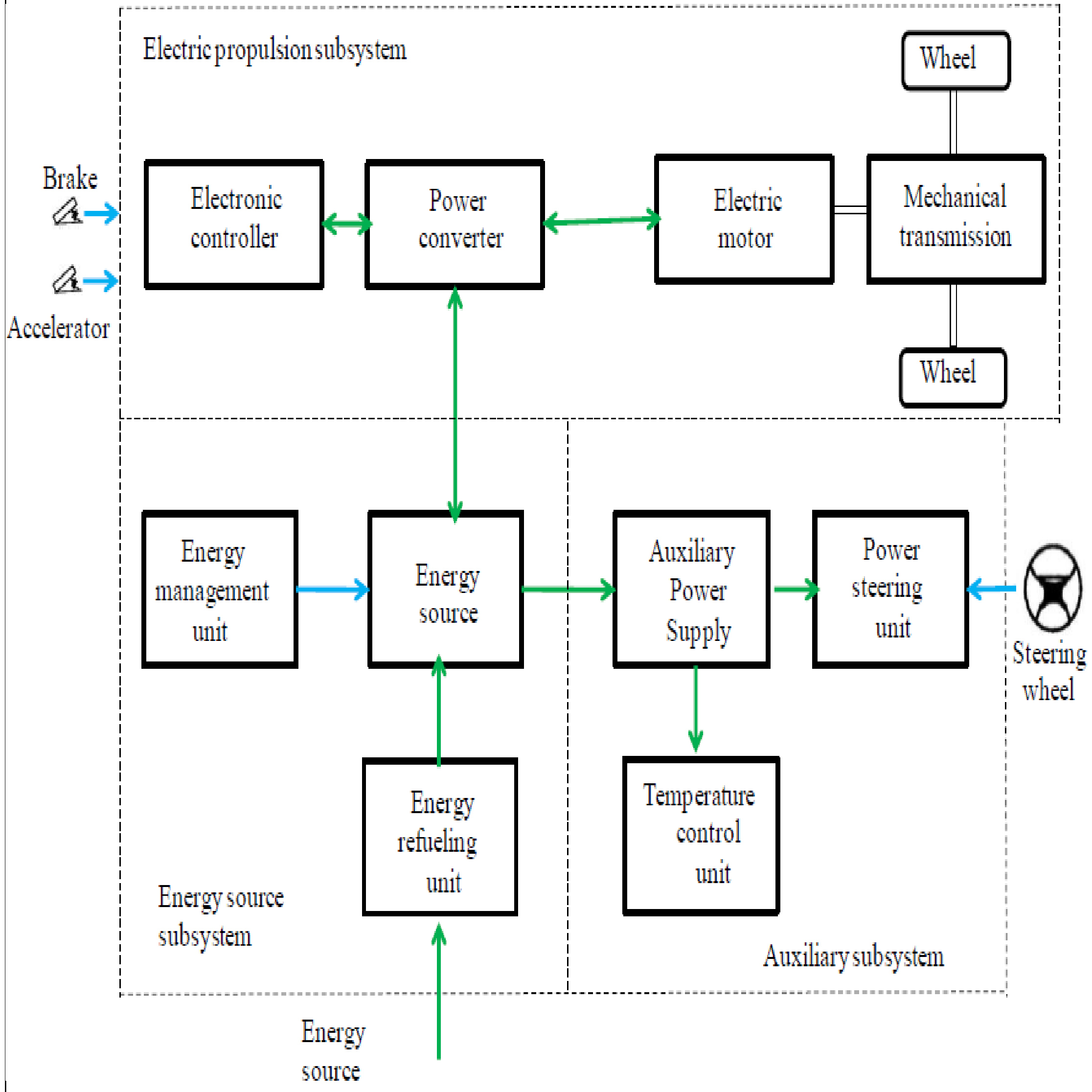


Figure A : General Configuration of a Electric Vehicle

- Black : mechanical link
- Green : electrical link
- Blue : control information communication
- Energy management unit cooperates with the electronic controller to control regenerative braking and its energy recovery
- The auxiliary power supply provides the necessary power with different voltage levels for all EV auxiliaries.

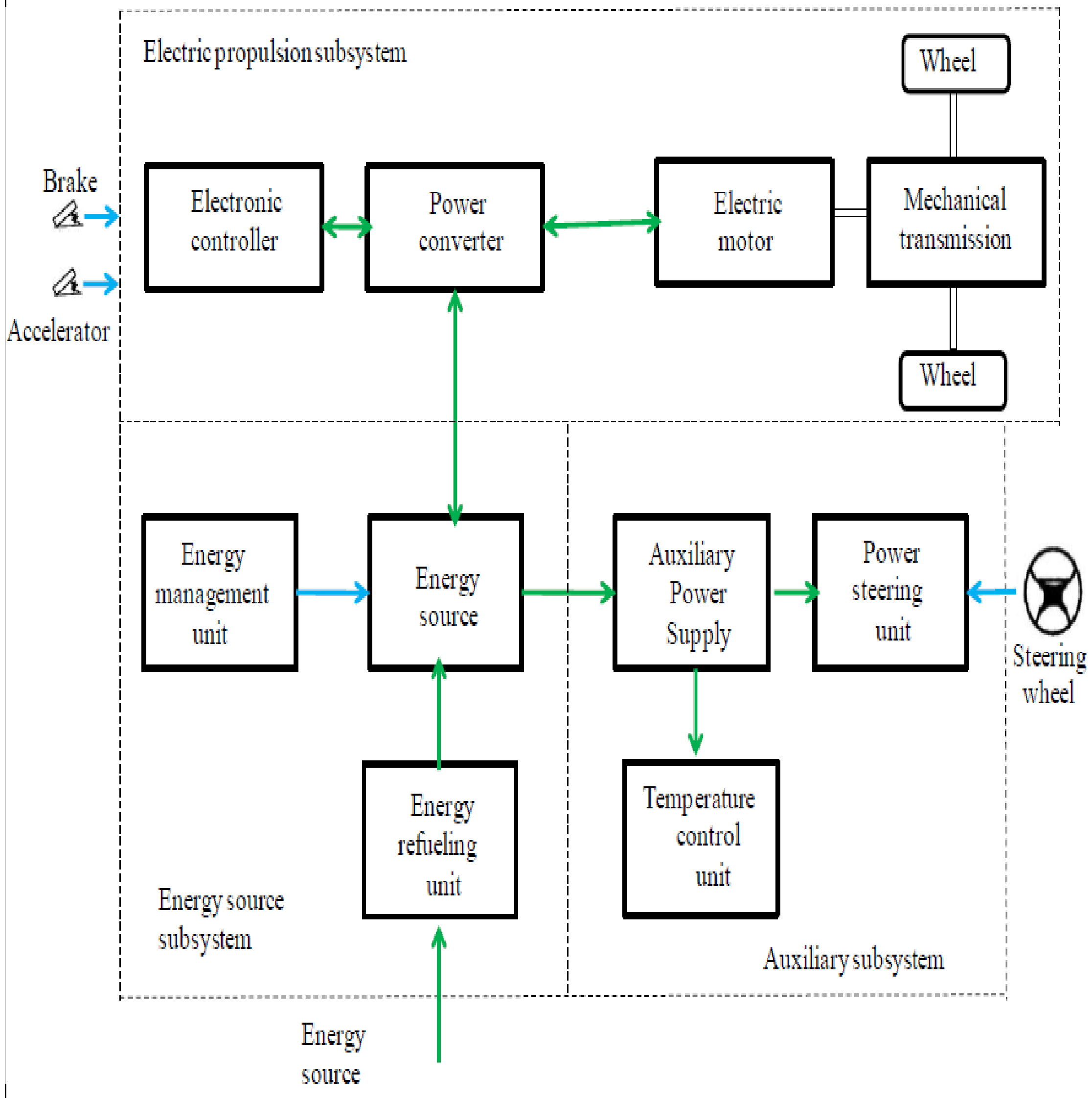


Figure A : General Configuration of a Electric Vehicle

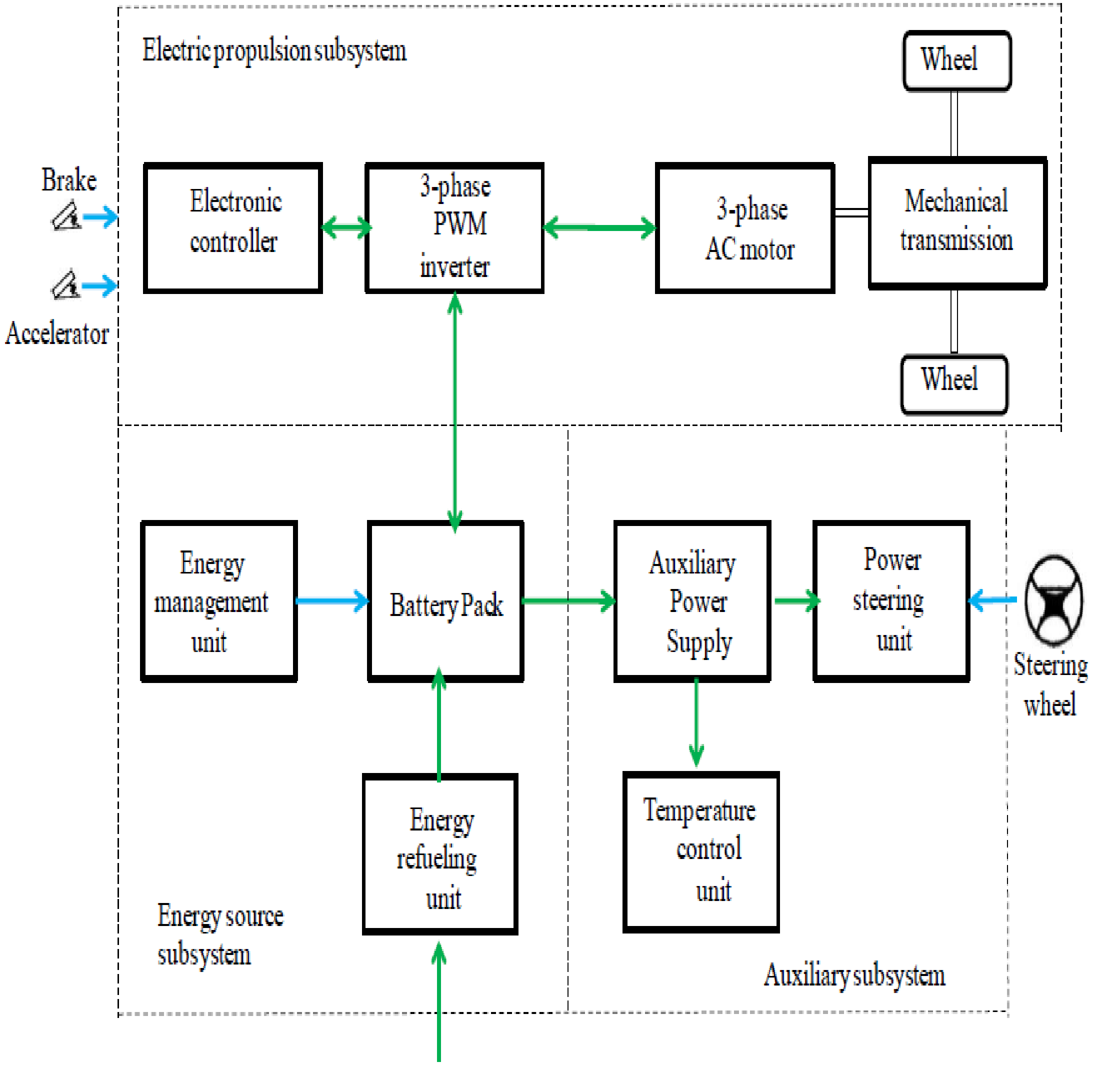
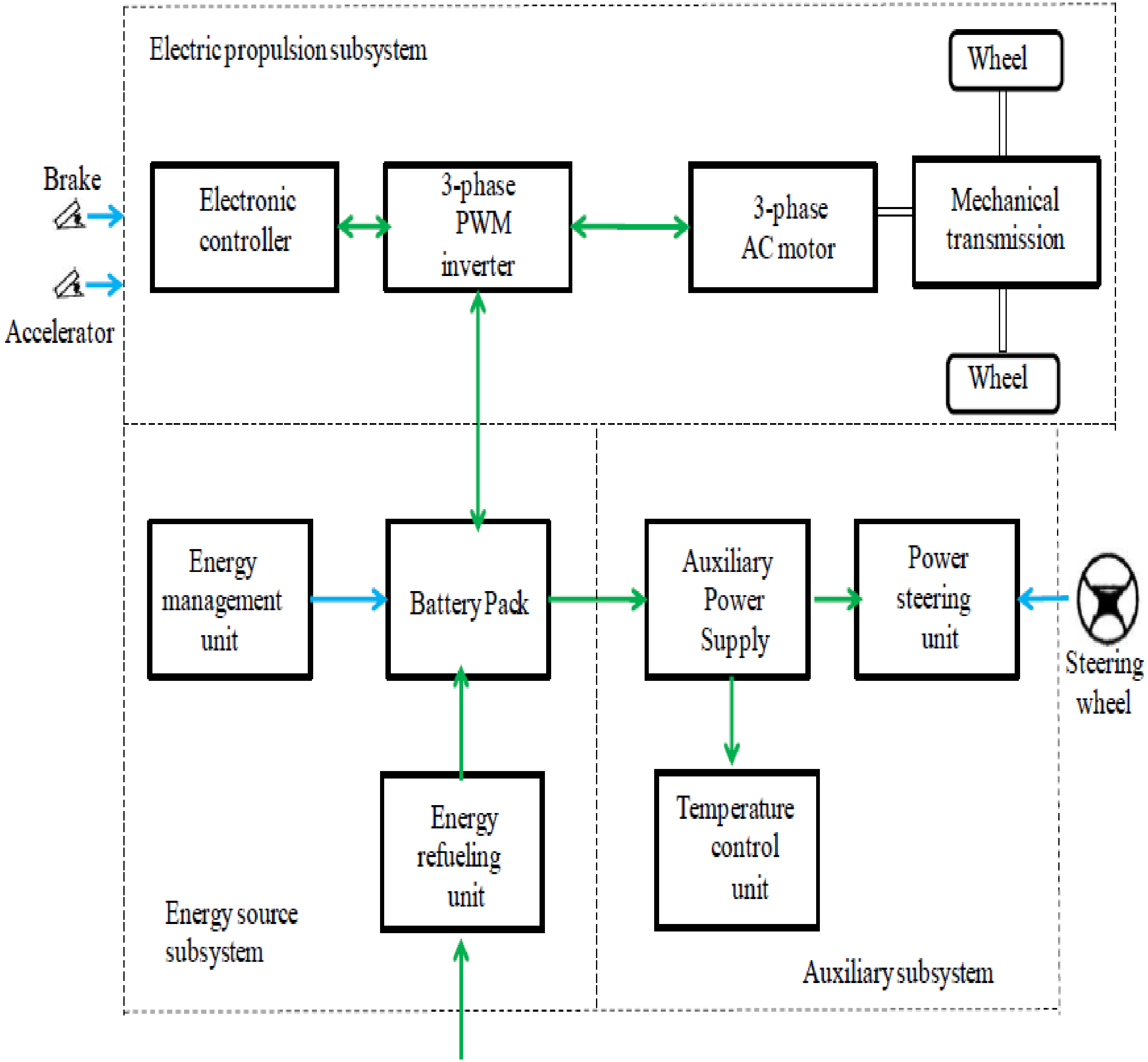


Figure B: Typical Configuration of a Electric Vehicle

- In modern EV’s configuration:
  - Three phase motors are generally used to provide the traction force
  - The power converter is a three-phase PWM inverter
  - Mechanical transmission is based on fixed gearing and a differential
  - Li-ion battery is typically selected as the energy source

The typical setup of the EV is shown in here:



Electric Vehicle (EV) Drivetrain Alternatives Based on Drivetrain Configuration

Variations in electric propulsion and energy sources

1. *1st configuration*: **Figure 3a :**
   - **C**lutch- connect or disconnect power flow from EM to wheels
   - Different gear ratios- driver can shift the gear ratios and torque going to the wheels can be changed.
   - High torque low speed in the lower gears
   - High-speed low torque in the higher gears.
   - The advantage of this configuration is that the weight of the transmission
2. In **Figure 3b**
   - Without the gearbox & clutch, Fixed Gearing
   - Weight of transmission is reduced
   - Demands more complex control of the EM
3. In **Figure 3c**
   - Transverse front EM front wheel drive configuration.
   - Fixed gearing & differential and they are integrated into a single assembly

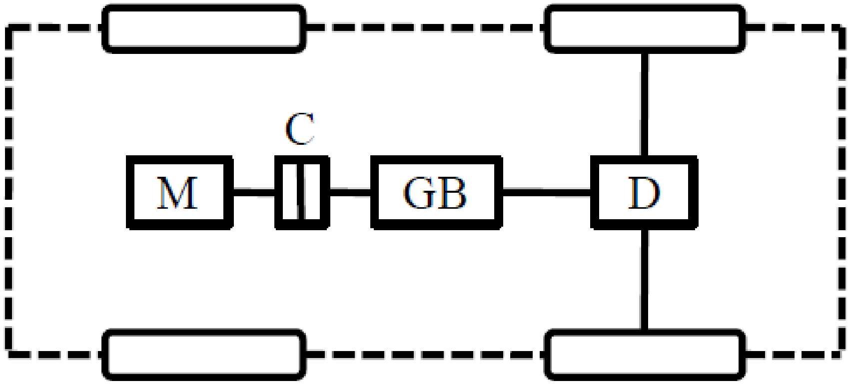


Figure 3a: EV configuration with clutch, gearbox and differential

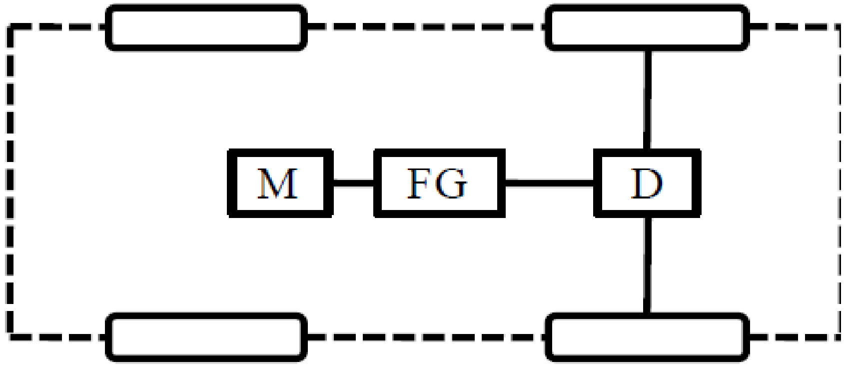


Figure 3b: EV configuration without clutch and gearbox [1]

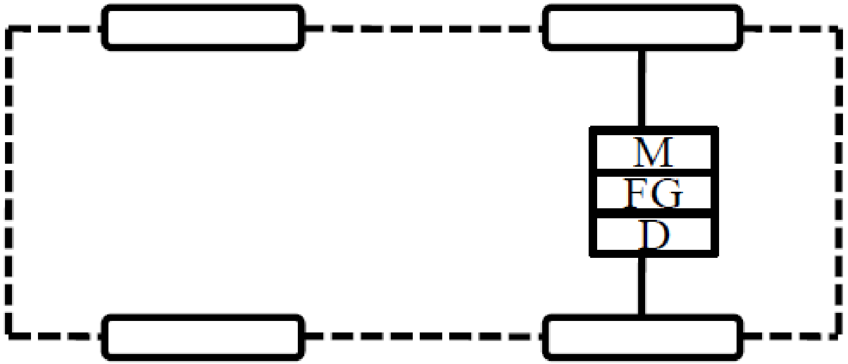


Figure 3c:EV configuration with clutch, gearbox and differential

4. In **Figure 3d**

- Dual motor configuration
- Differential action of an EV when cornering can be electronically provided by 2 electric motors.

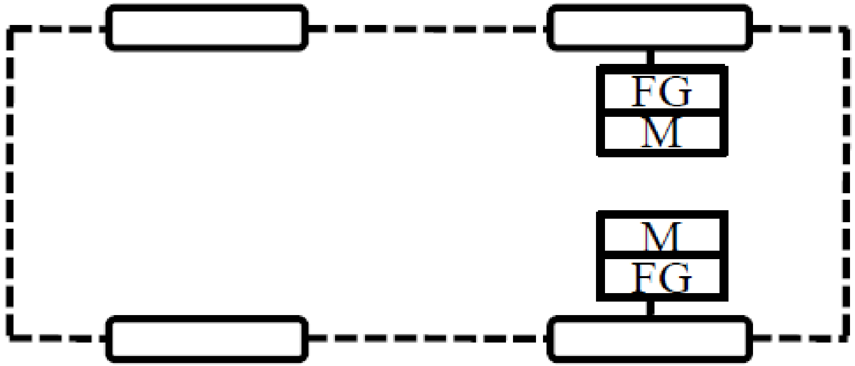


Figure 3d:EV configuration with two EM [1]

5. In **Figure 3e**

- To shorten the mechanical transmission path from the EM to the driving wheel, the EM can be placed inside a wheel.
- *In-wheel drive*
- Fixed gearing to reduce the motor speed.

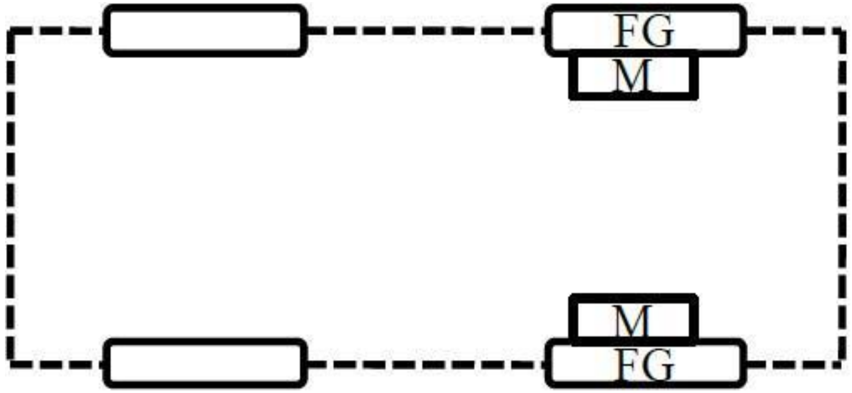


Figure 3e:EV configuration with in wheel motor and mechanical gear [1]

6. In **Figure 3f**

- Without any mechanical gearing
- In-wheel drive can be realized by installing a low speed outer-rotor electric motor inside a wheel.

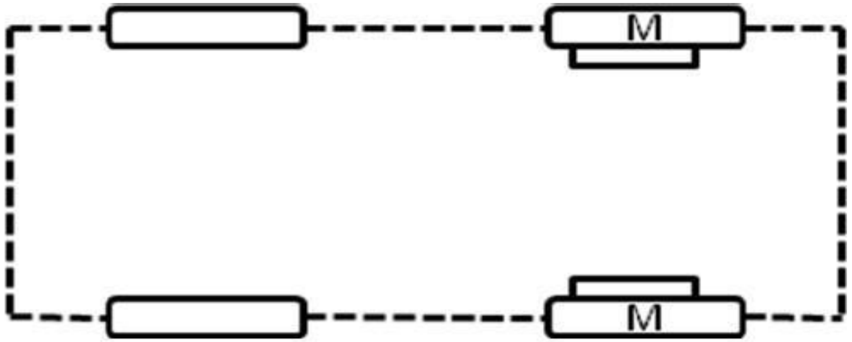
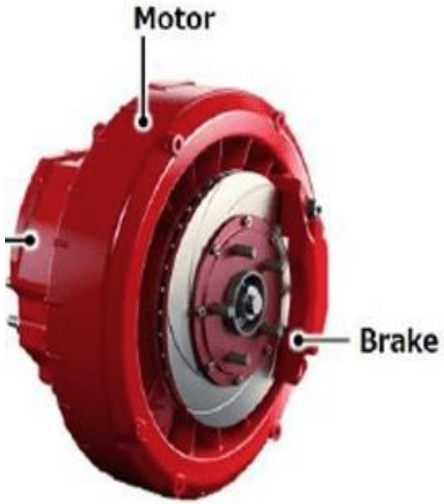


Figure 3f:EV configuration with in wheel motor and no mechanical gear [1]

C: Clutch
D: Differential
FG: Fixed gearing

GB: Gearbox
EM: Electric motor

In-wheel drive



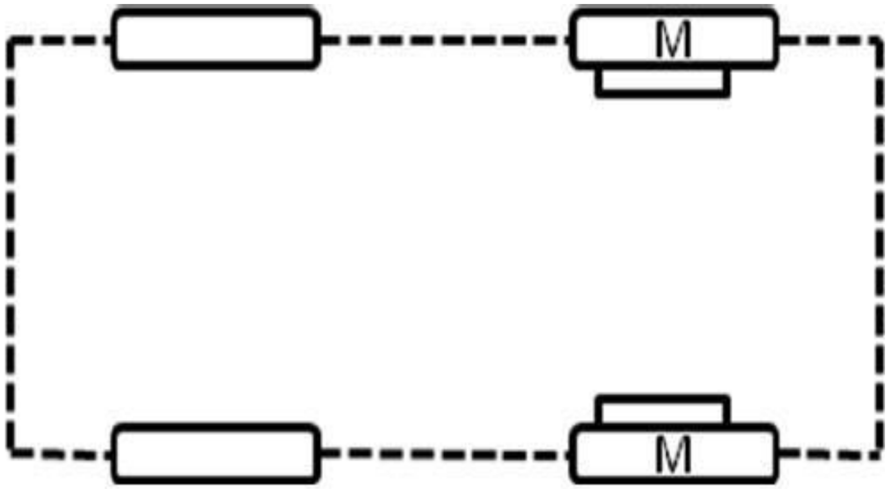


Figure 3f:EV configuration with in wheel motor and no mechanical gear [1]

In Future cars won’t be called as

CARS

but ???

COWS

COMPUTERS ON WHEELS

EV Drivetrain Alternatives Based on *Power Source Configuration*

Variations in energy sources:

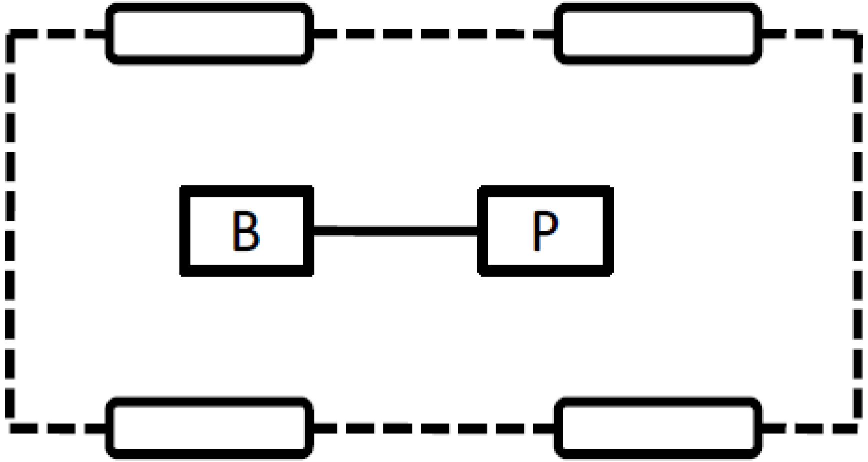


Figure 4a: EV configuration with battery source [1]

1. Configuration 1: **Figure 4a:**

- **S**imple battery powered configuration
- **B** - distributed around vehicle, packed together at the vehicle back or located beneath chassis.
- Have high specific energy, specific power and able to accept regenerative energy.
- High specific power governs the driving range while the high power density governs the acceleration rate and hill climbing capability.

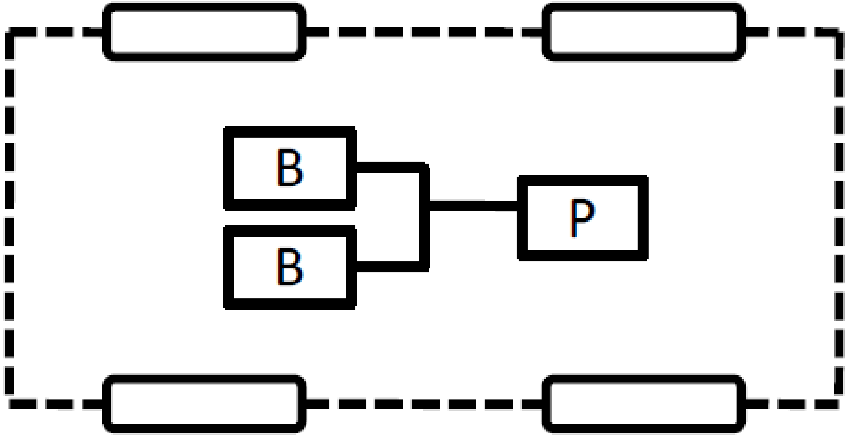


Figure 4b: EV configuration with two battery sources [1]

2. Configuration 2: **Figure 4b:**

- Uses two different batteries,.
- One **B** for high specific energy & other for high specific power.

B: Battery
C: Capacitor
FC: Fuel cell
FW: Flywheel
P: Power converter
R: Reformer

3. Configuration 3: **Figure 4c:**

- Fuel cell is used
- **B-** energy storage device, **FC-** energy generation device.
- **FC-** reverse process of electrolysis
- Hydrogen and oxygen gases combine to form electricity and water.
- Hydrogen gas stored in an on-board tank
- Oxygen gas is extracted from air
- FC offer high specific energy - cannot accept regenerative energy, it is preferable to combine it with battery with high specific power and high-energy receptivity.

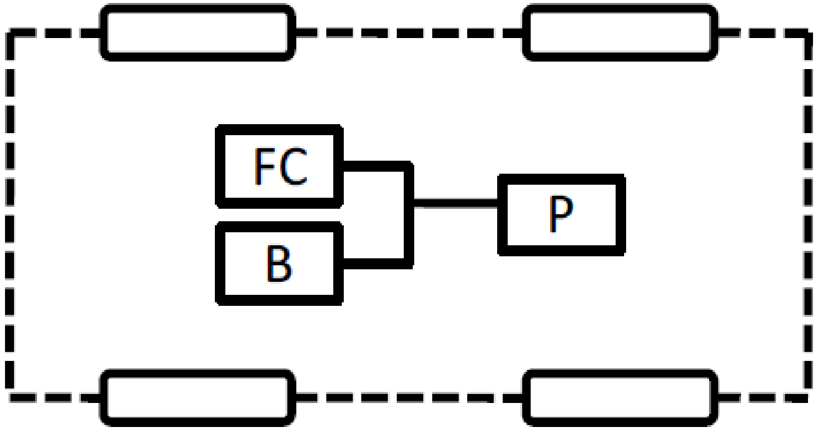


Figure 4c: EV configuration with battery and fuel cell sources [1]

4. Configuration 4: **Figure 4d.**

- Rather than storing it as a compressed gas, a liquid or a metal hydride, hydrogen can be can be generated on-board using liquid fuels such as methanol
- In this case ***a mini reformer*** is installed in the EV to produce necessary hydrogen gas for **FC.**

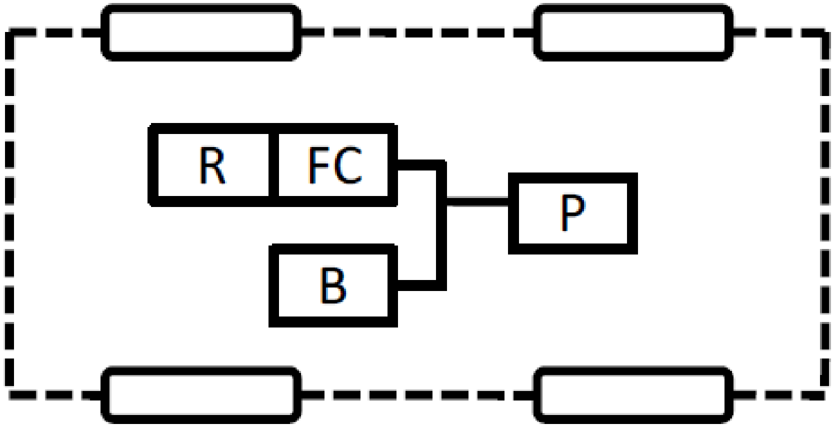


Figure 4d: EV configuration with multiple energy sources [1]

5. Configuration 5: **Figure 4e:**

- Battery and *supercapacitor* is used as an energy source
- **B** is a high energy density device
- Supercapacitor provides high specific power and energy receptivity.
- Supercapacitors are of relatively low voltage levels, an additional dc-dc power converter is needed to interface between the battery and capacitor terminals.

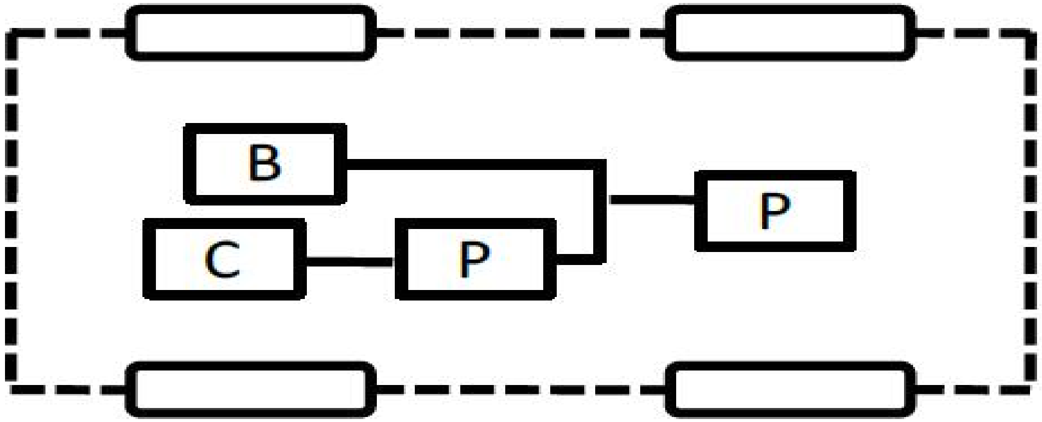


Figure 4e: EV configuration with battery and capacitors sources [1]

“A supercapacitor with the same power is three times lighter than the normal lithium-ion battery”

Single and Multi-motor Drives

- When a vehicle is rounding a curved road, the outer wheel - larger radius than the inner wheel.
- Differential adjusts the relative speeds of the wheels.
- If relative speeds of the wheels are not adjusted, wheels will slip and result in tire wear, steering difficulties and poor road holding.
- In EVs, it is possible to dispense the mechanical differential by using two or even four EMs.
- With the use of multiple EMs, each wheel can be coupled to an EM and this will enable independent control of speed of each (electronically achieved).
- In **Figure 5**, dual motor drive with an electronic differential is shown.

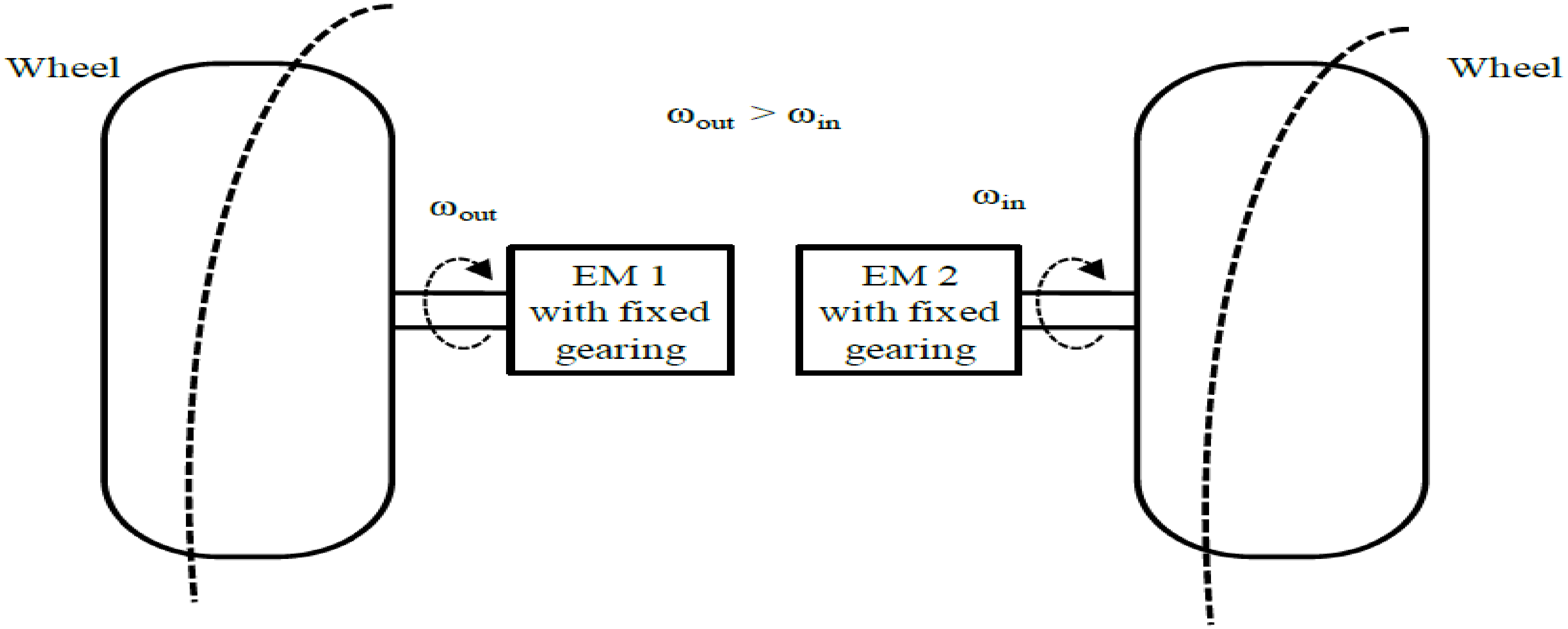


Figure 5: Differential action [1]

In Wheel Drives

- Electric motor inside the wheel
- Advantage : mechanical transmission path between EM & wheel can be minimized. Two possible configurations for in wheel drives are:
- When a high-speed inner-rotor motor is used (**Figure 6a**) then a fixed speed-reduction gear becomes necessary to attain a realistic wheel speed. Speed reduction is achieved using a planetary gear set. This motor is designed to operate up to 1000 rpm so as to give high power density.
- In case outer rotor motor is used (**Figure 6b**), transmission can be totally removed and the outer rotor acts as the wheel rim and the motor speed is equivalent to the wheel speed and no gears are required.

High-speed inner rotor motor are:

- It has the advantage of smaller size, lighter weight and lower cost
- Needs additional planetary gear set

Outer-rotor motor are

- Low speed and hence does not need additional gears
- The drawbacks are larger size, weight and cost because of the low speed design.

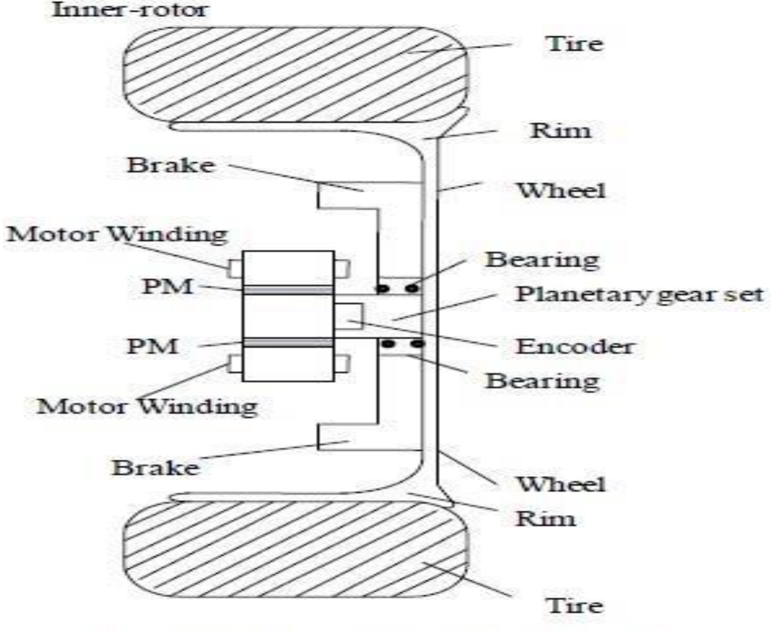


Figure 6a: Inner rotor *In Wheel* drive [1]

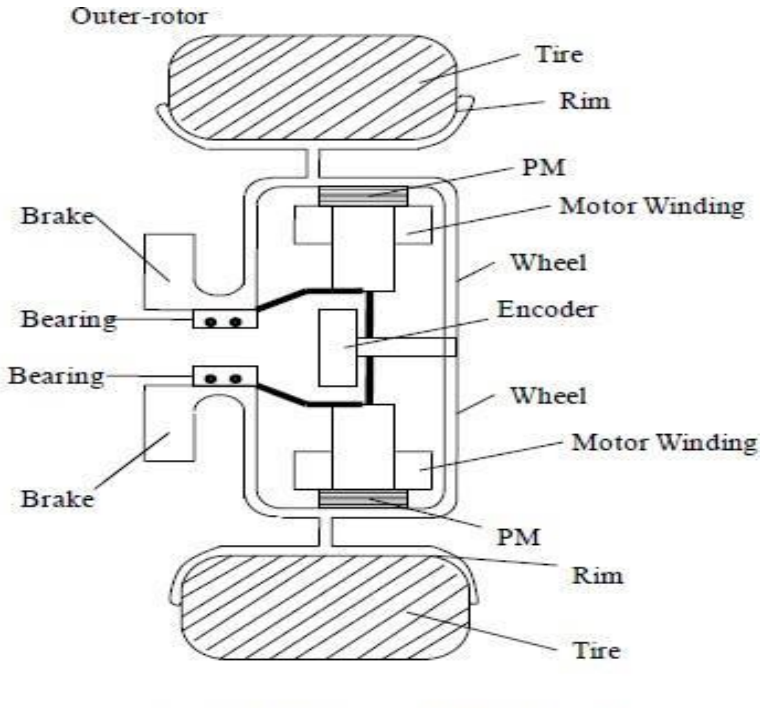
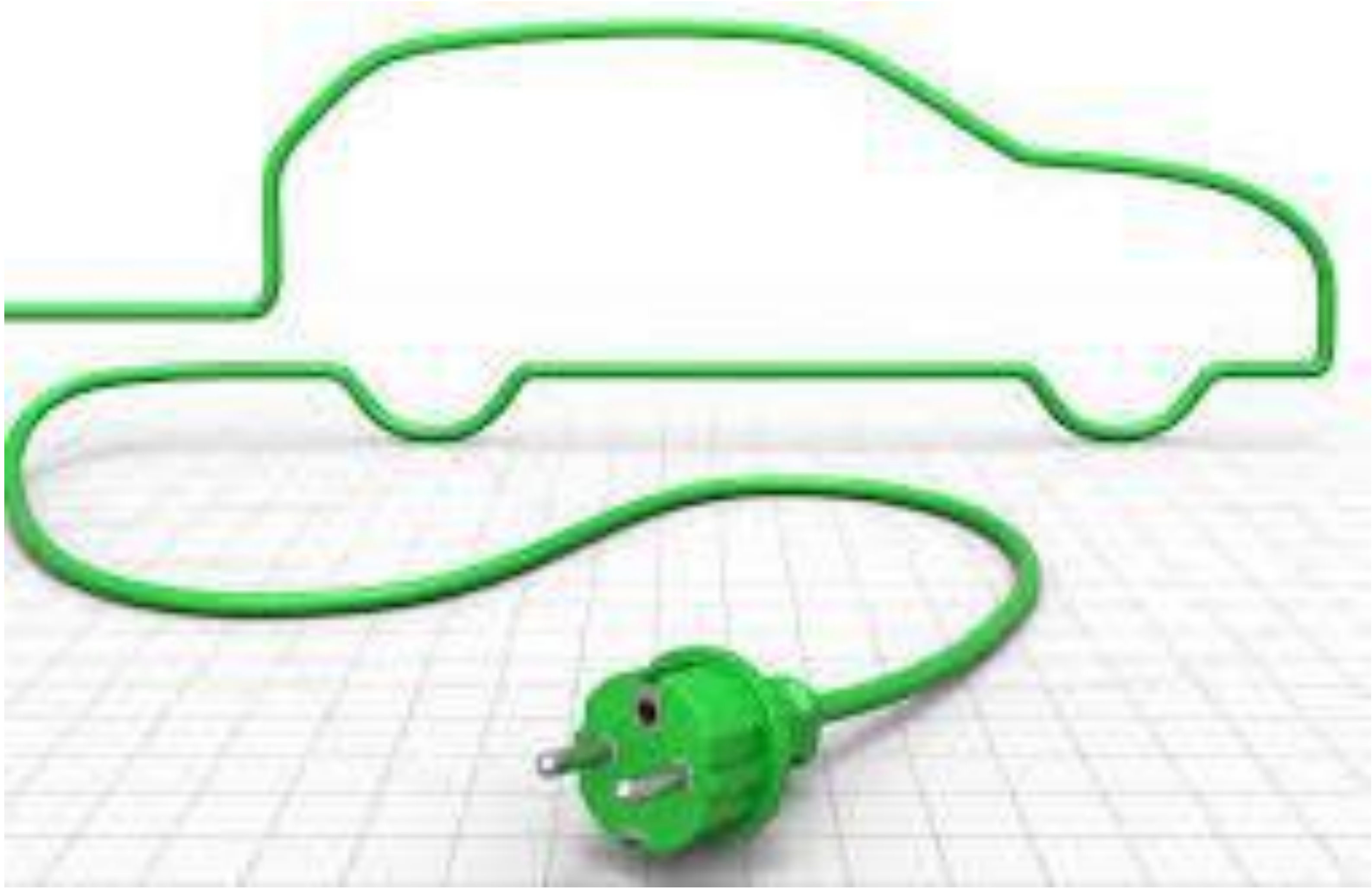


Figure 6b: Outer rotor *In Wheel* drive [1]

EE469: Electric & Hybrid Vehicles



<u>Module 3</u>

III	Electric Propulsion unit: Introduction to electric components used in hybrid and electric vehicles, Configuration and control of DC Motor drives, Configuration and control of Induction Motor drives	**7**	15%

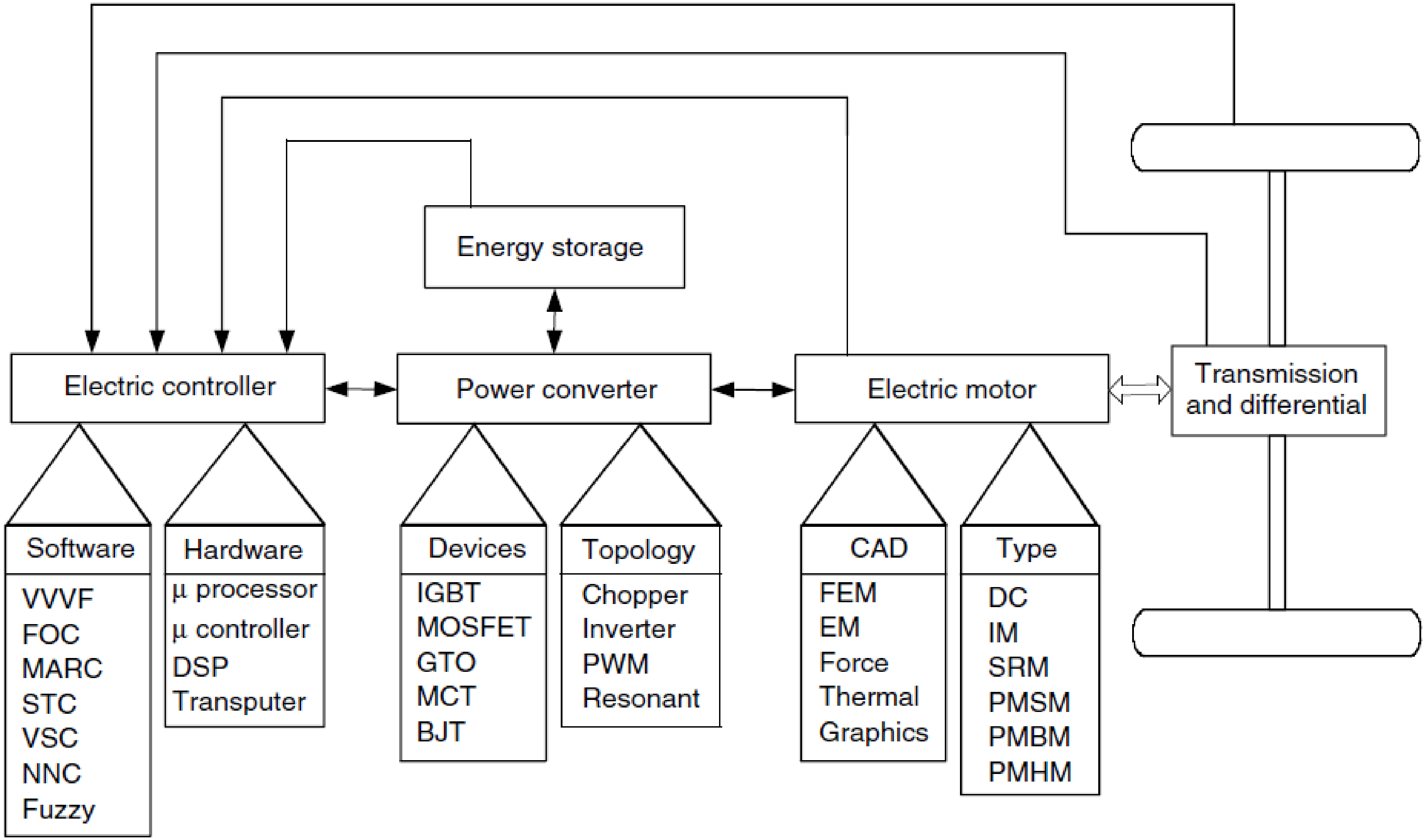


FIGURE 3.1 Functional block diagram of a typical electric propulsion system

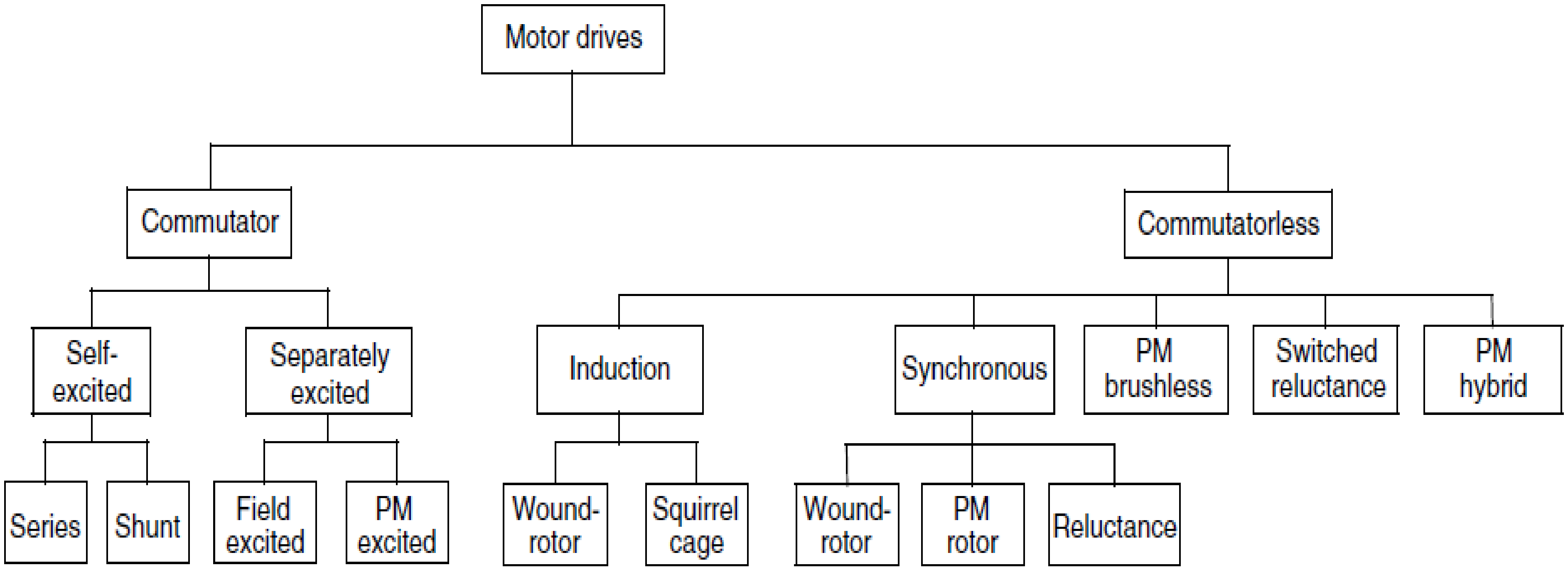
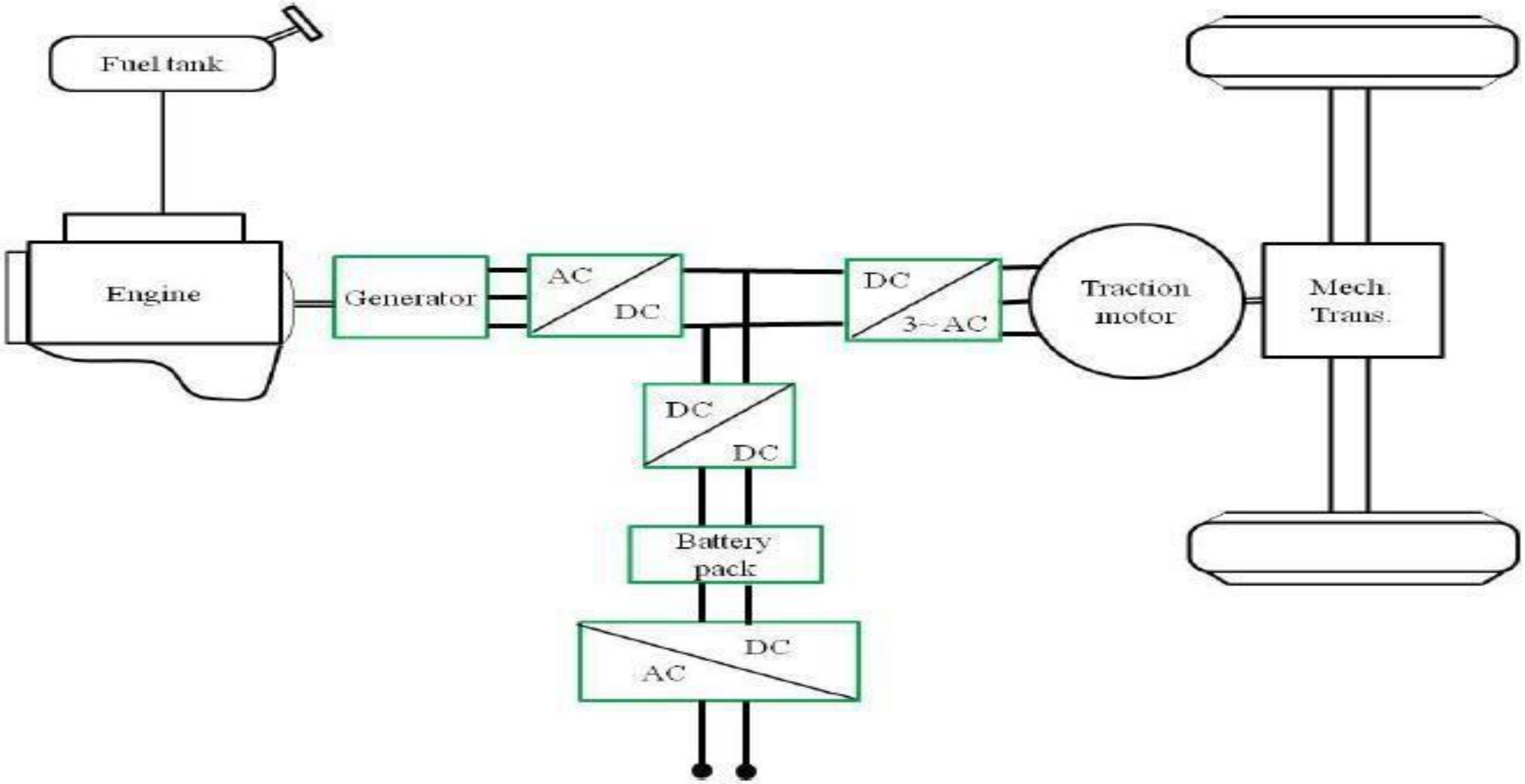


fig 3.2: Classification of electric motor drives for EV and HEV applications



Configuration of a Electric Vehicle:

Electric Vehicle (EV) and Hybrid Electric Vehicle (HEV) Configurations

- 2 major power electronic units

  -DC converter

  -AC inverter

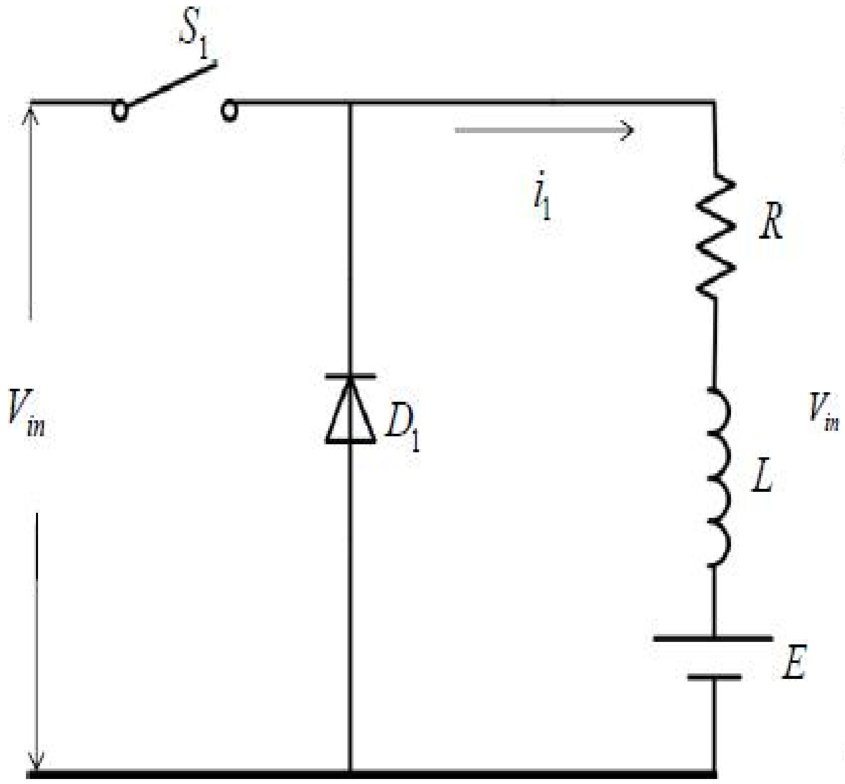
Unidirectional Converters: They cater to various onboard loads such as sensors, controls, entertainment, utility and safety equipments.

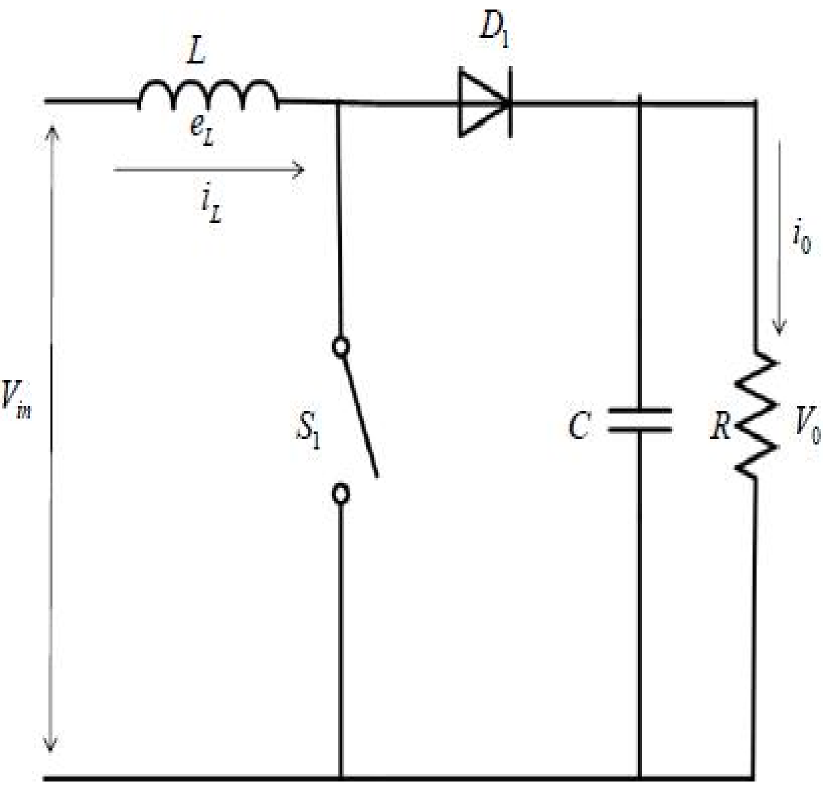
Bidirectional Converters: They are used in places where battery charging and regenerative braking is required.

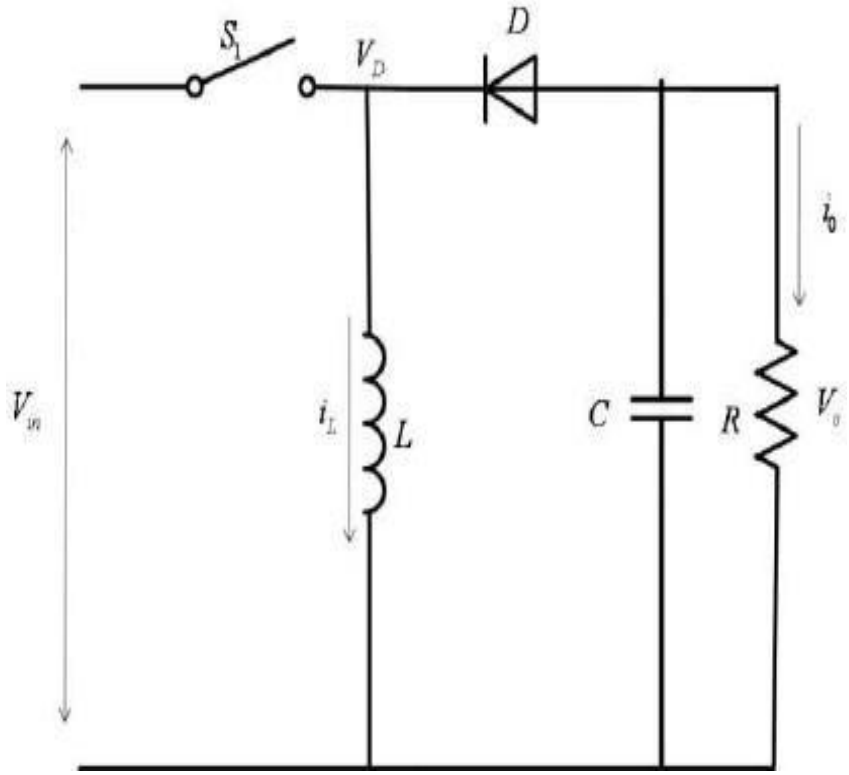
- To isolate the circuit, *High Frequency Transformers* are used.

Classification of Converters

- **Buck Converter:** ***Step down Converter***
- **Boost converter:** ***Step Up Converter***
- **Buck-Boost converter:** The output voltage can be either higher or lower than the input voltage.

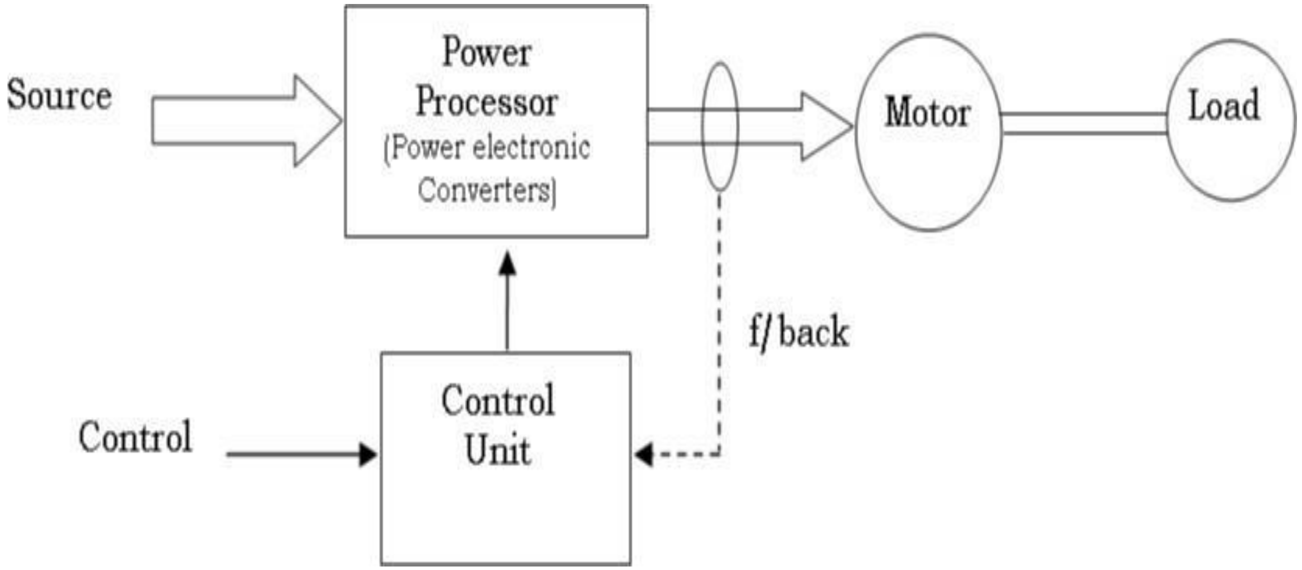






Electric Drives

- Motion control - drives.
- 50% e.e produced is used in electric drives.



Components in Electric Drives

—*Motors*

- DC motors - permanent magnet – wound field
- AC motors – induction, synchronous , brushless DC

—*Power sources*

- DC – batteries, fuel cell, photovoltaic
- AC – Single- three- phase utility, wind generator

—*Power Converters*

Advantages of Electric Drives

- Flexible control characteristics.
- Starting and braking is easy and simple
- Provides a wide range of torques over a wide range of speeds (both ac and dc motor)
- Availability of wide range of electric power
- Works to almost any type of environmental conditions
- No exhaust gases emitted
- Capable of operating in all 4 quadrants of torque–speed plane. Can be started and accelerated at very short time

- **APPLICATIONS OF ELECTRIC DRIVES**

- Transportation system, rolling mills, paper mills, textile mills, machine tools, fans, pumps, robots, washing machines etc.
- Motion control may be translational, rotational or combination of both.
- Drive system has a mechanical load, a transmission system and a prime mover

DC Motor Drives

- Electric drives that use DC motors as the prime movers are called as DC motor drive.
- **DC motor drives** are used mainly for good speed regulation, frequent starting, braking and reversing.
- Speed control are normally simpler and less expensive than those of AC drives.
- DC motors are not suitable for very high speed applications and require more maintenance than AC motors.

1. By varying the resistance in the armature circuit (Rheostatic control)
2. By varying the flux (flux control)
3. By varying the applied voltage (voltage control)

Types of DC drives

1.Phase controlled rectifier fed DC drives
  a.According to the input supply
    i.Single phase rectifier fed DC drives
    ii.Three phase rectifier fed DC drives
  b.According to the quadrant operation
    i.One quadrant operation
    ii.Two quadrant operation
    iii.Four quadrant operation

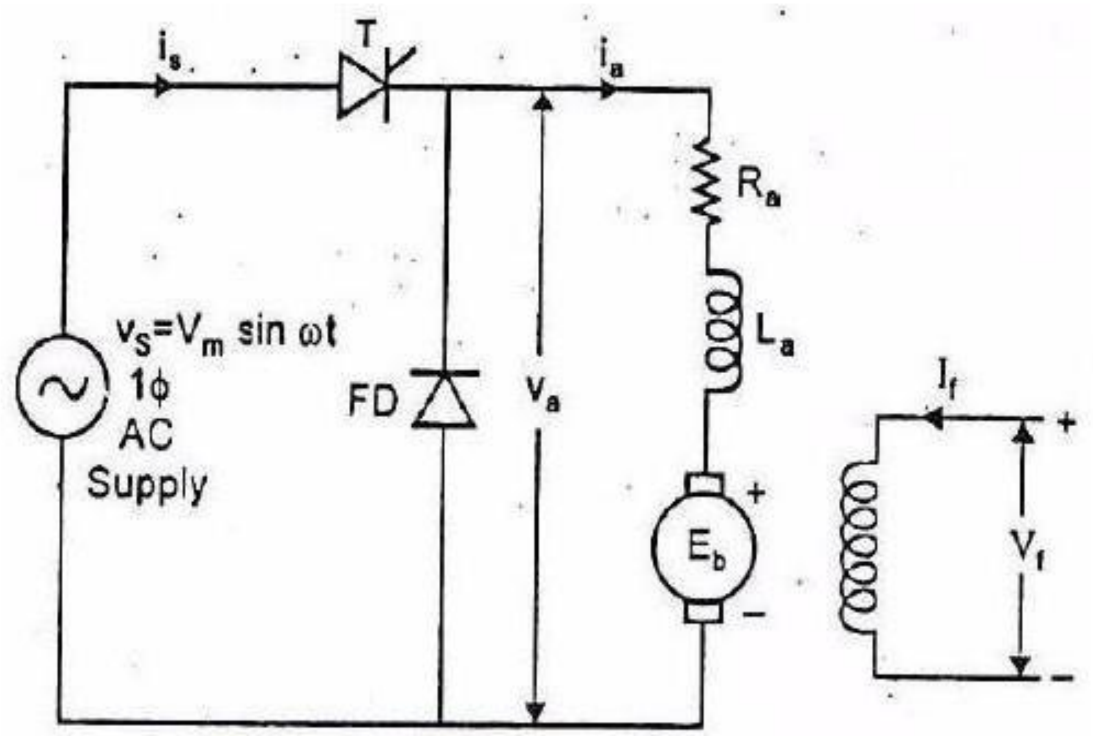
2.Chopper fed DC drives
  i.One quadrant chopper drives
  ii.Two quadrant chopper drives
  iii. Four quadrant chopper drives

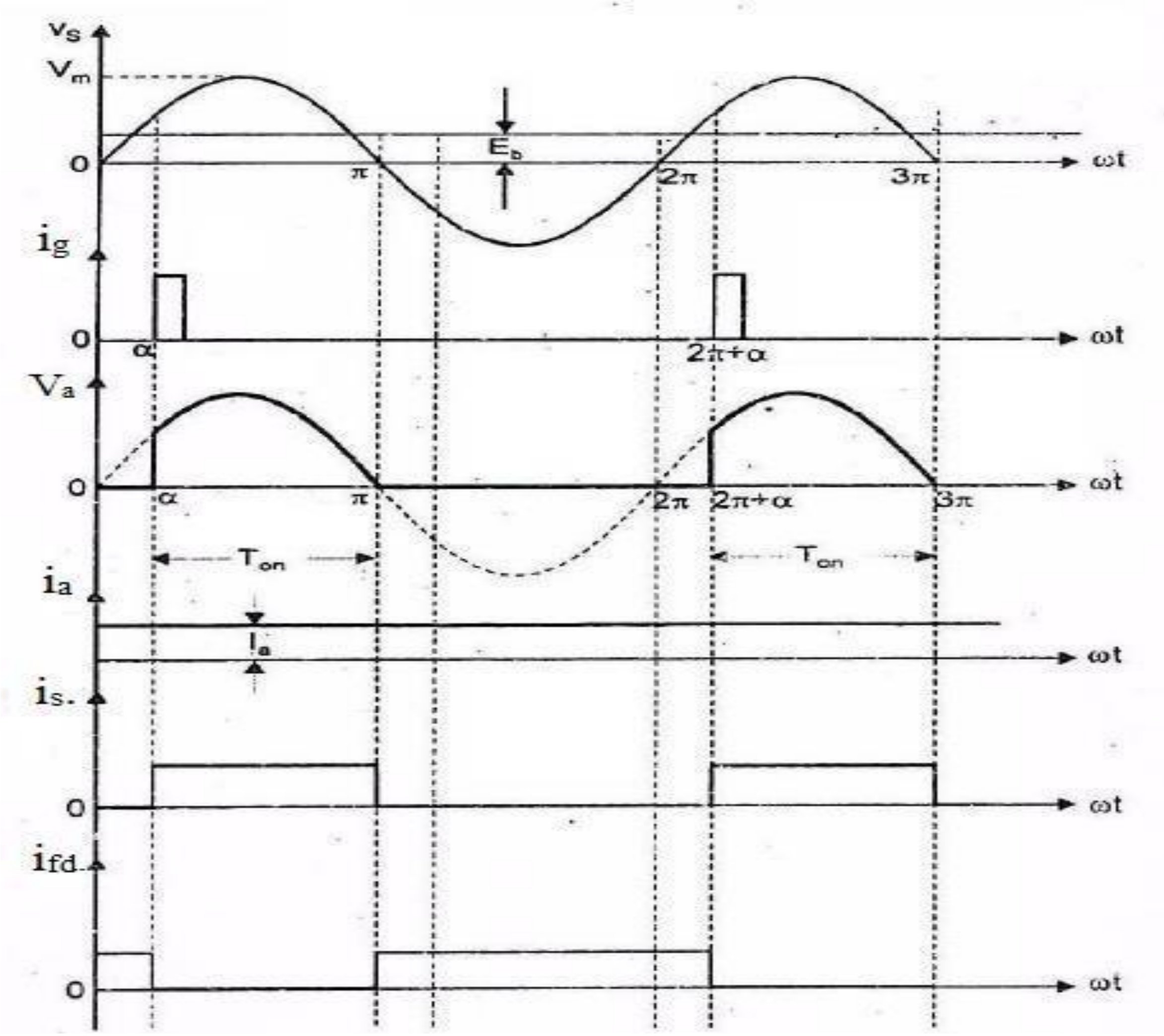
Single-phase drives may be subdivided into

- Ø Single-phase half-wave-converter drives.
- Ø Single-phase full-converter drives.
- Ø Single-phase dual-converter drives.

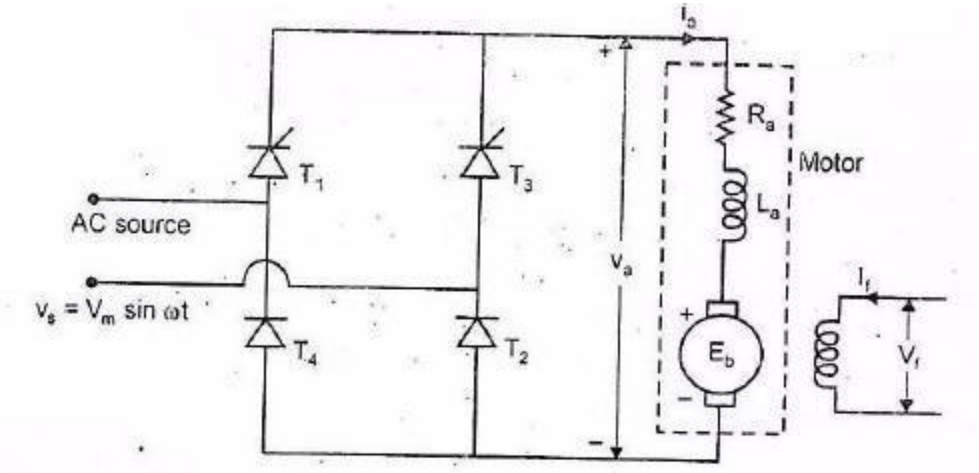
Types of DC drives in details

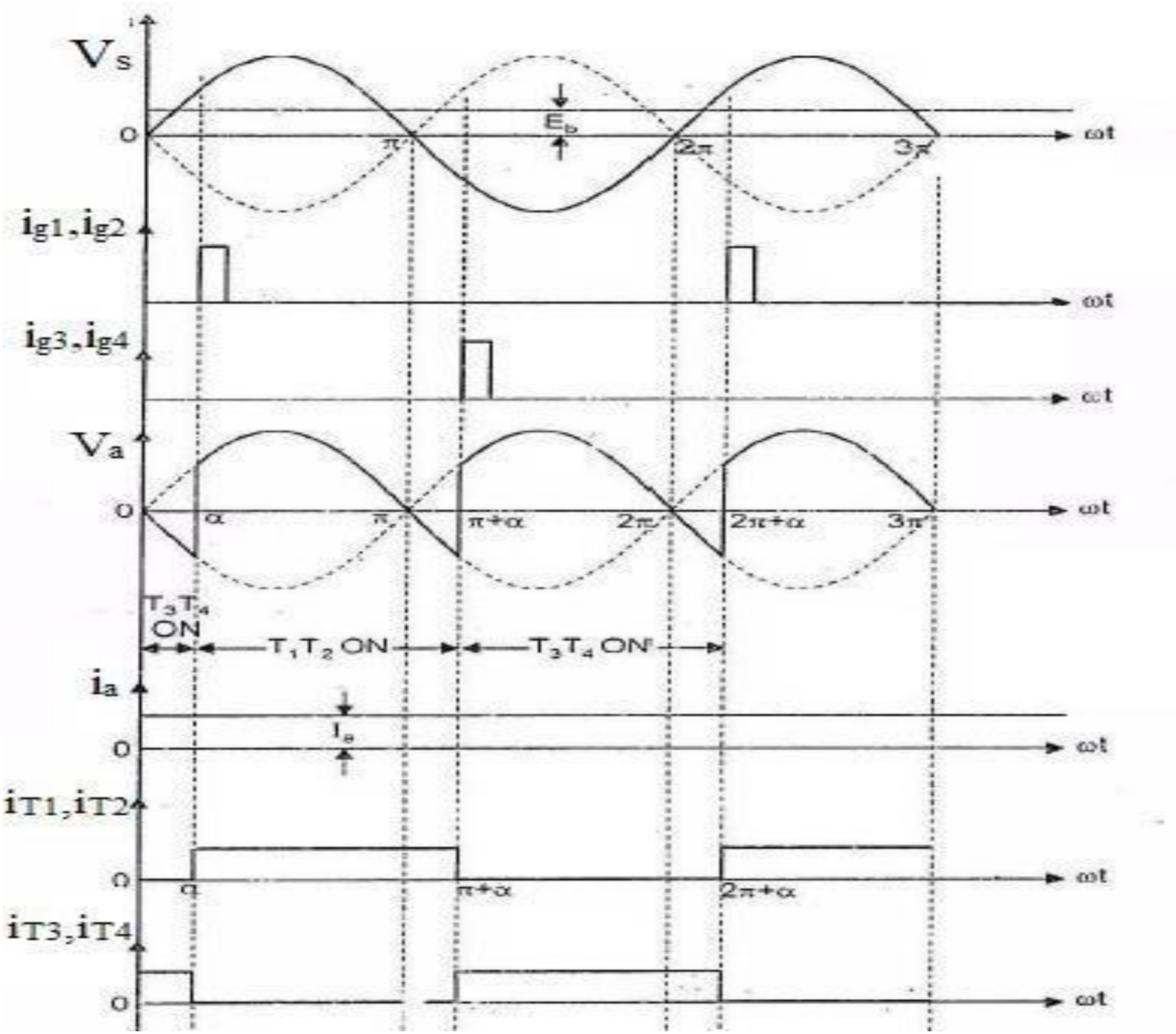
Single Phase Half wave controlled Rectifier fed DC Drives (one quadrant converter)



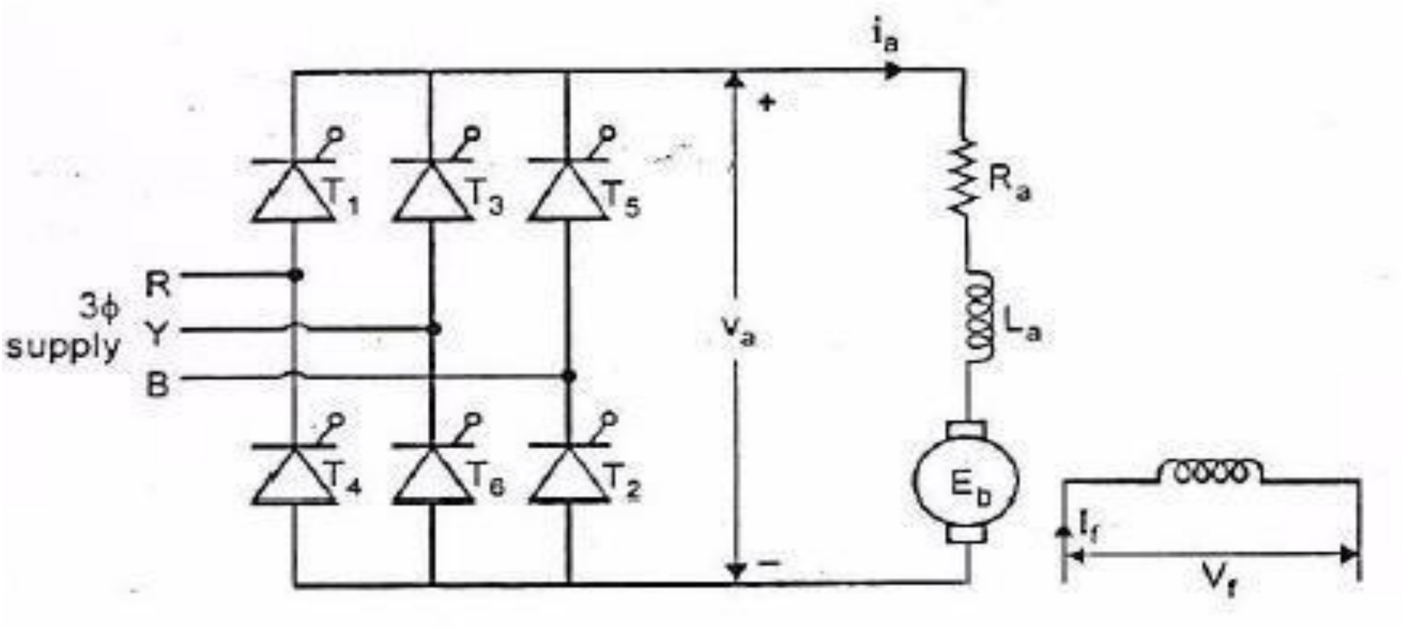


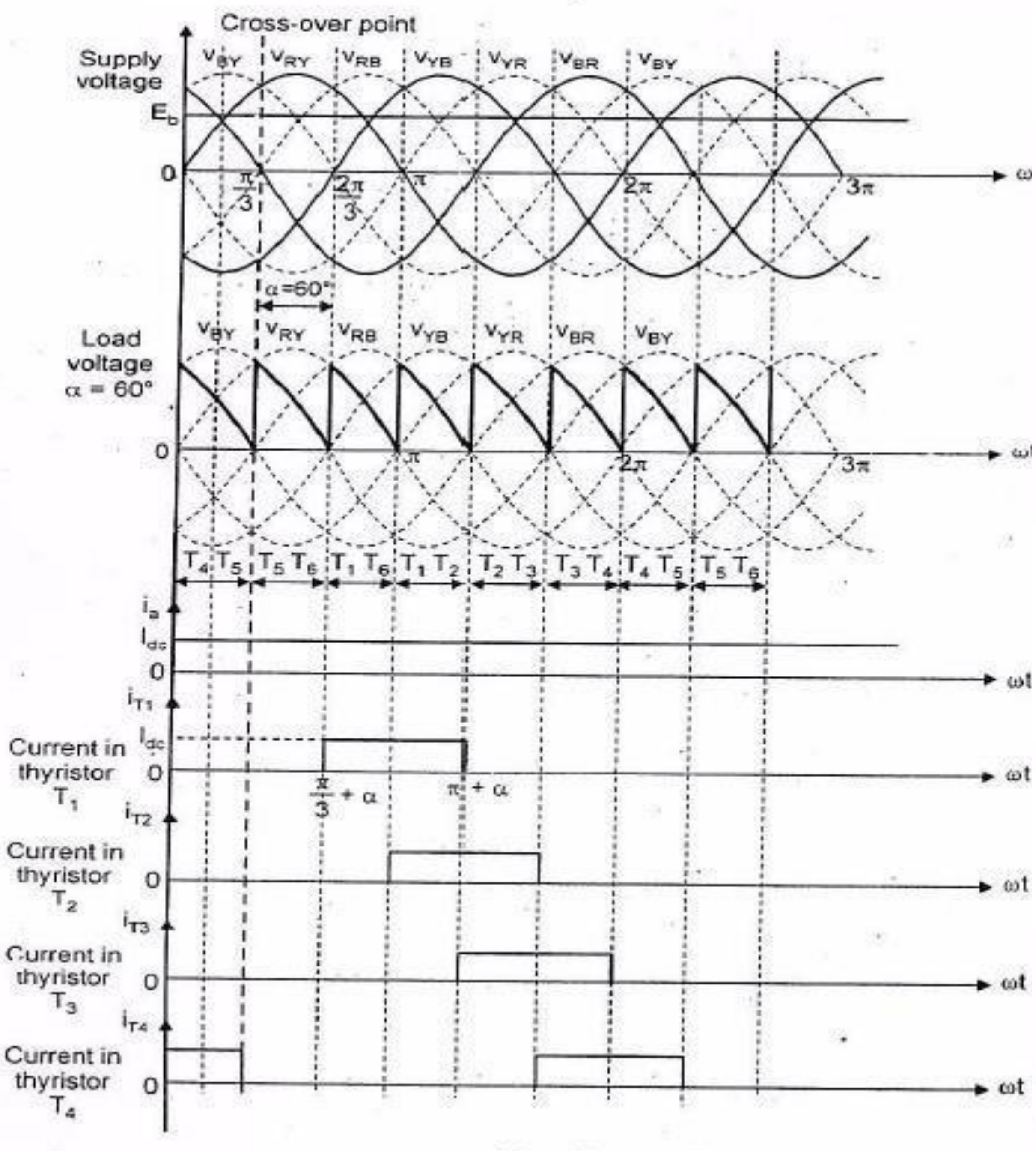
Single phase fully controlled rectifier fed DC drives



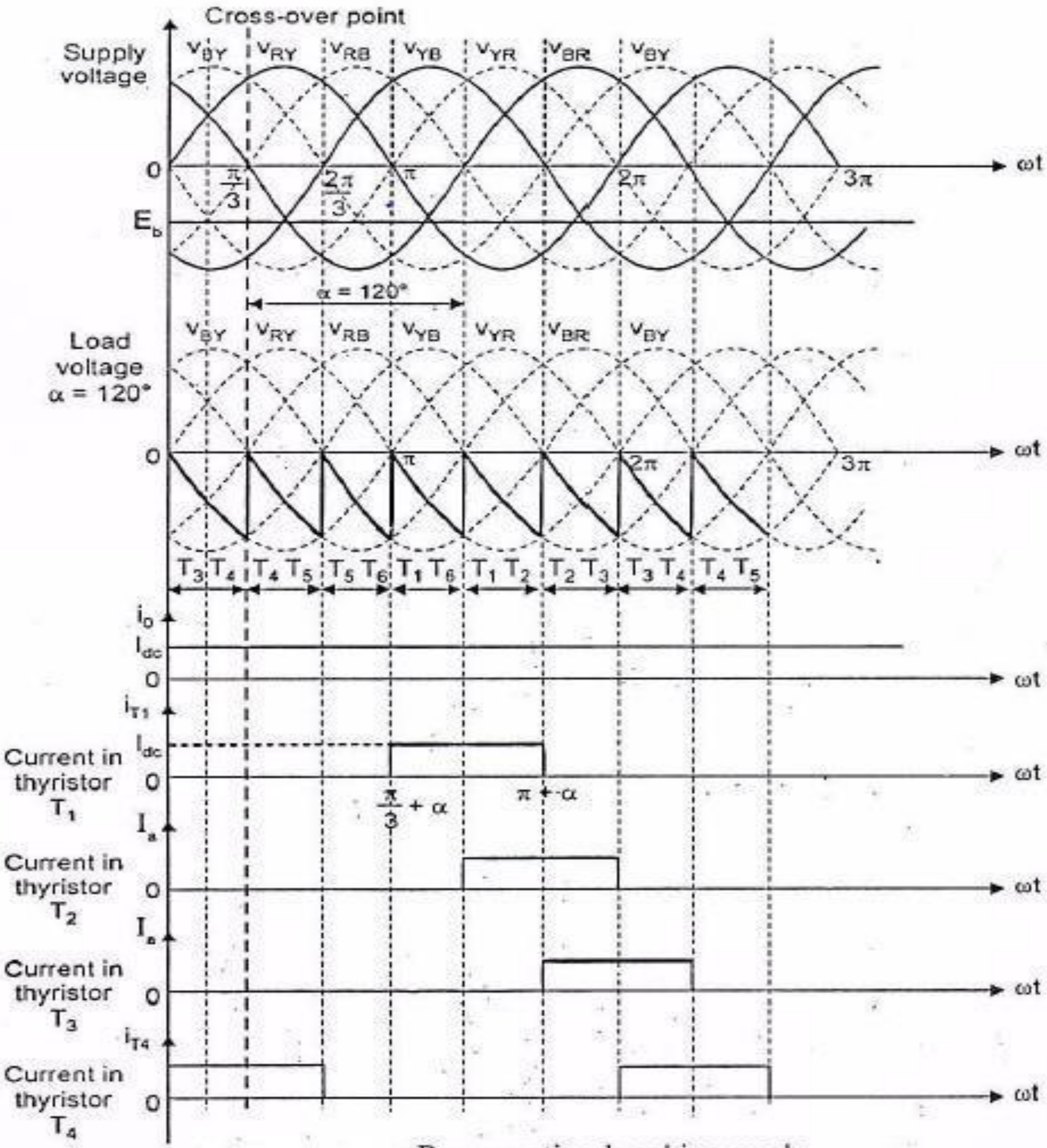


Three phase fully controlled rectifier fed separately excited DC motor drive.





Motoring mode

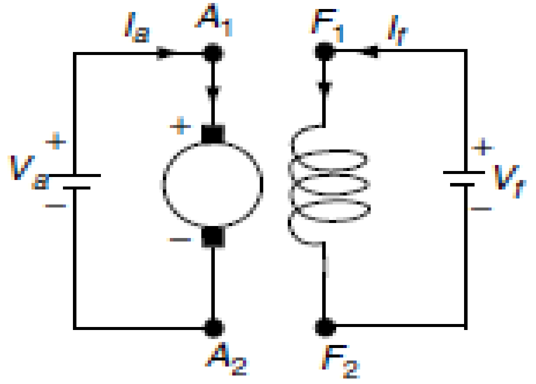


Regenerative breaking mode

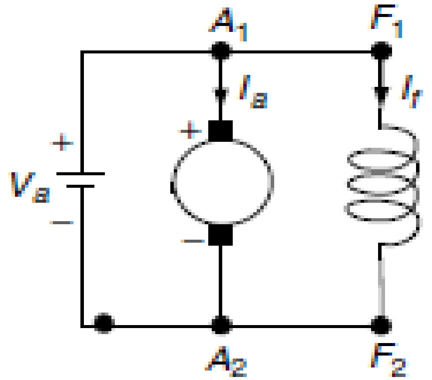
DC motor:

A dc motor may be operating in one or more modes:

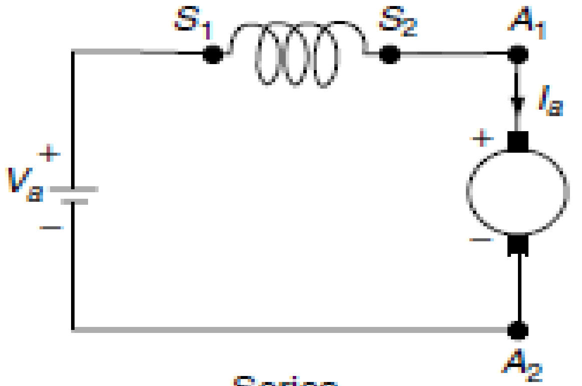
- –motoring,
- –Regenerative braking,
- –dynamic braking,
- –plugging,
- –four quadrants.



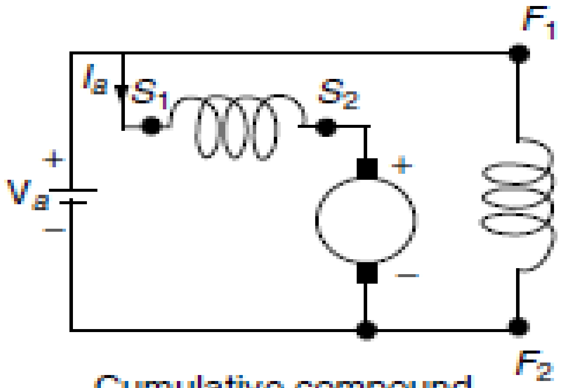
Separately



Shunt

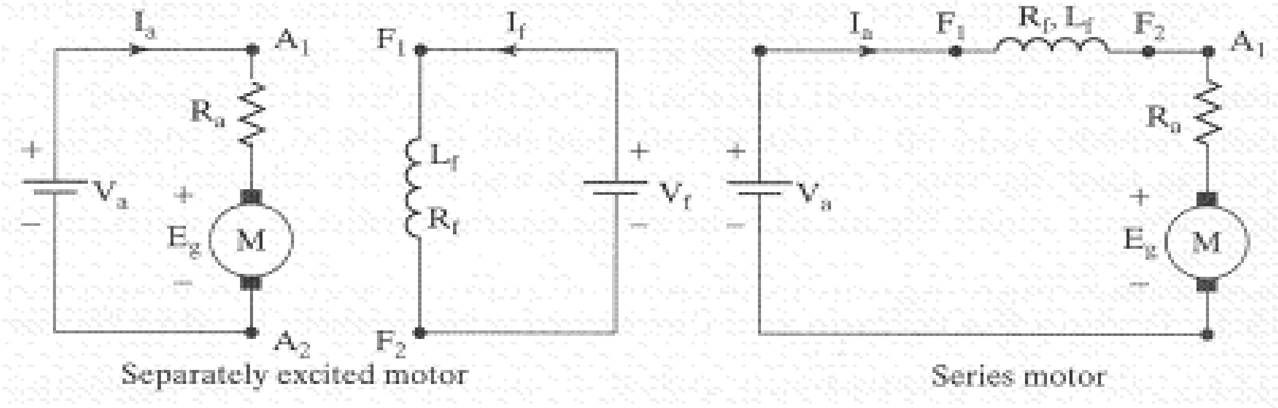


Series



Cumulative compound

Motoring: Back emf Eg is less than supply voltage Va. Both armature and field currents are positive. The motor develops torque to meet the load demand.

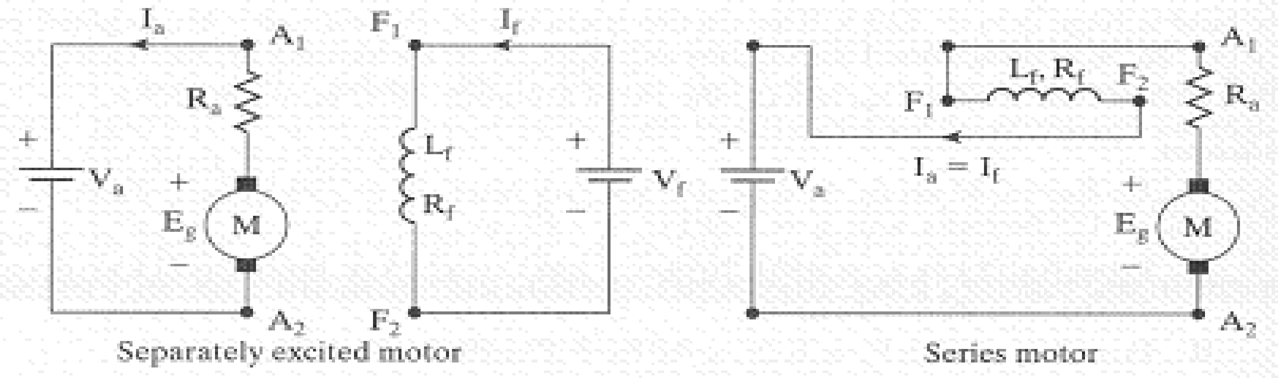


Separately excited motor

Series motor

(a) Motoring

Regenerative braking: The motor acts as a generator and develops an induced voltage Eg. Eg must be greater than supply voltage Va. The armature current is negative, but the field current is positive. The kinetic energy of the motor is returned to the supply. A series motor is usually connected as a self-excited generator.

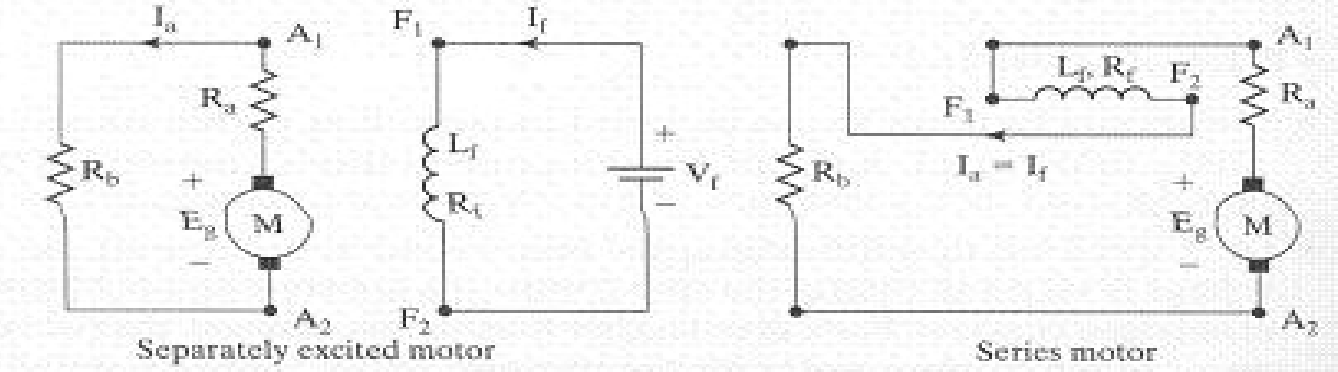


Separately excited motor

Series motor

(b) Regenerative braking

Dynamic braking: The arrangements shown in Figure c are similar to those of regenerative braking, except the supply voltage Va is replaced by a braking resistance Rb, The kinetic energy of the motor is dissipated in Rb.

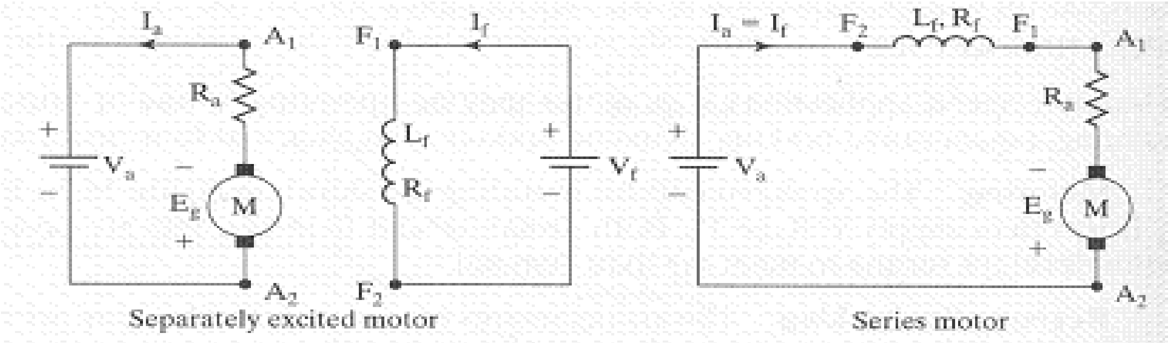


Separately excited motor

Series motor

(c) Dynamic braking

Plugging: Plugging is a type of braking. The connections for plugging are shown in Figure d. The armature terminals are reversed while running. The supply voltage Va and the induced voltage Eg act in the same direction. The armature current is reversed, thereby producing a braking torque. The field current is positive.



Separately excited motor

Series motor

(d) Plugging

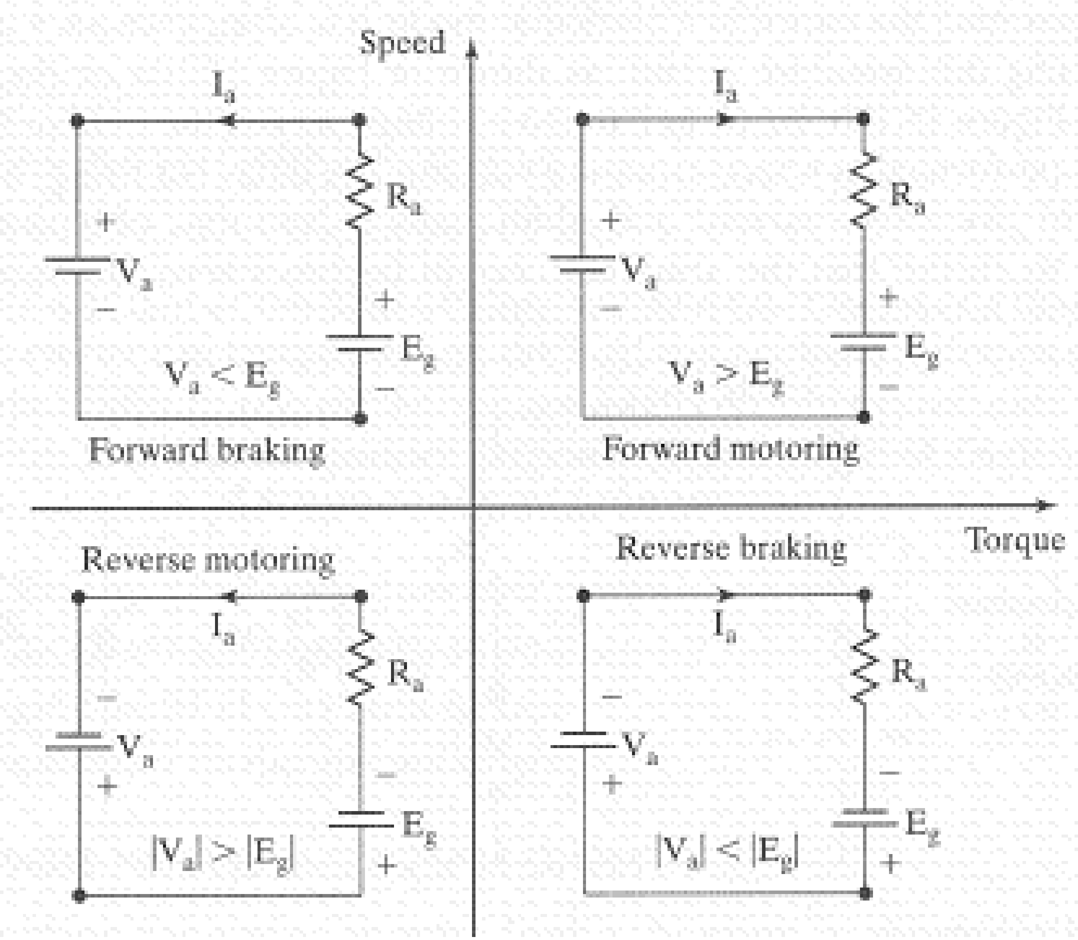
***Four Quadrants*:**

- Forward motoring (Qua I) **: Va, Eg,, T, N and Ia are all positive**.

- Forward braking (Qua II): motor runs in the forward direction and the induced emf Eg continues to be positive. Torque to be negative and the direction of energy flow to reverse, the armature current must be negative.

- Reverse motoring (Qua III) : Va, Eg, and Ia are all negative. Torque and speed are also negative in this quadrant.

- Reverse braking (Qua IV): motor runs in the reverse direction. Va, and Eg continue to be negative. torque to be positive and the armature current must be positive.



Induction motor drives

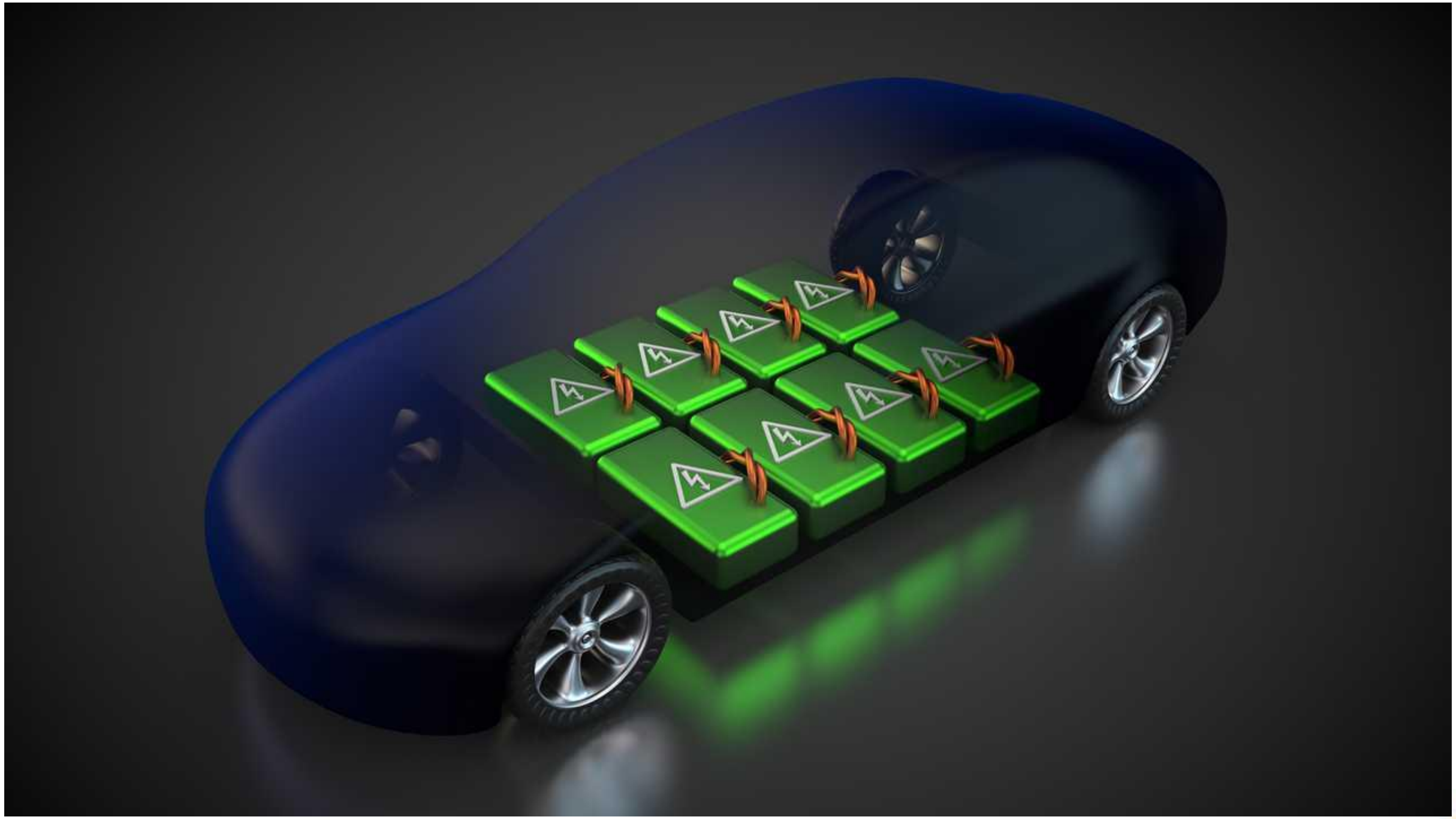
Commutatorless motor drives offer a number of advantages over conventional DC commutator motor drives for the electric propulsion of EVs and HEVs. At present, induction motor drives are the mature technology among commutatorless motor drives. Compared with DC motor drives, the AC induction motor drive has additional advantages such as ***lightweight nature, small volume, low cost, and high efficiency.*** These advantages are particularly important for EV and HEV applications.

There are two types of induction motors, namely, wound-rotor and squirrel cage motors. Because of the high cost, need for maintenance, and lack of sturdiness, wound-rotor induction motors are less attractive than their ***squirrel-cage*** counterparts, especially for electric propulsion in EVs and HEVs.

EE469: Electric & Hybrid Vehicles

__Module 4__

IV	Energy Storage: Introduction to Energy Storage Requirements in Hybrid and Electric Vehicles, Battery based energy storage and its analysis, Fuel Cell based energy storage and its analysis, Hybridization of different energy storage devices.	**7**	15%

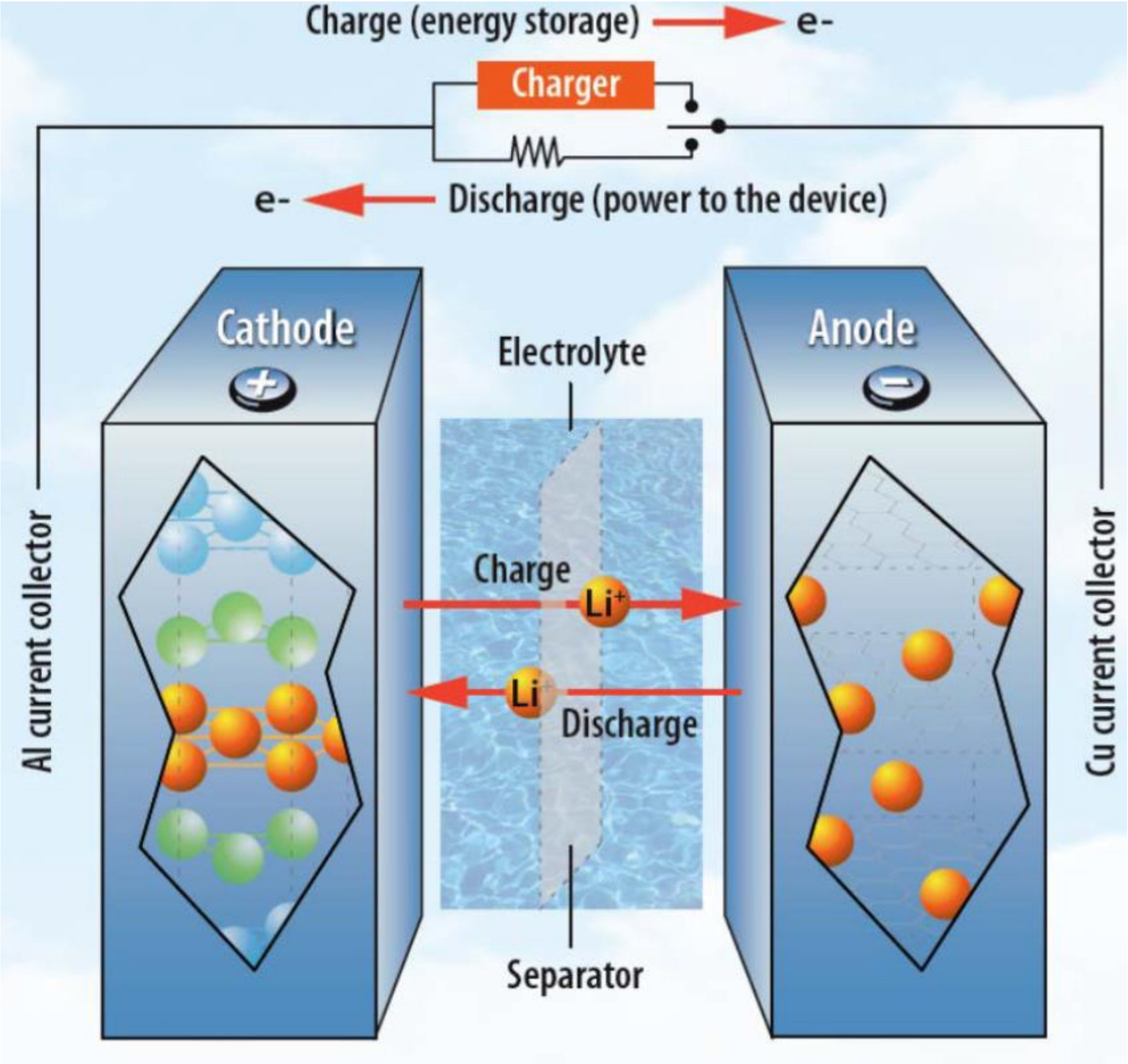


BATTERY FUNDAMENTALS

BATTERY PRINCIPLE

- **A suitable combination of negative and positive electrode materials must exist to provide potential difference.**

- **Potential difference = $E_{cathode}$ - E_{anode}**



Source : Argonne National Laboratory

ENERGY STORAGE : Batteries

- ***Battery*** : two or more electric cells joined together.
- Cells convert ***chemical*** energy to ***electrical*** energy. Cells consist of positive and negative electrodes joined by an electrolyte. Chemical reaction between electrodes and electrolyte which generates DC electricity.
- In secondary or rechargeable batteries, the chemical reaction can be reversed by reversing the current and the battery returned to a charged state.
- ‘Lead acid’ battery is the most well known rechargeable type, but there are others.
- Lead acid, nickel iron, nickel cadmium, nickel metal hydride, lithium polymer and lithium iron, sodium sulphur and sodium metal chloride.
  - Battery Parameters
  - Lead acid batteries
  - Lithium ion batteries
  - Metal air batteries
  - Battery Charging

Overview of Batteries

Battery can be treated as a ‘black box’ which has a range of performance criteria. These criteria will include:

- specific energy
- specific power
- amp hour efficiency
- commercial availability
- self-discharge rates
- recharge rates

* energy density
* typical voltages
* energy efficiency
* cost, operating temperatures
* number of life cycles

How energy availability varies with regard to:

- ambient temperature
- battery geometry
- charging methods

* charge and discharge rates
* optimum temperature
* cooling needs.

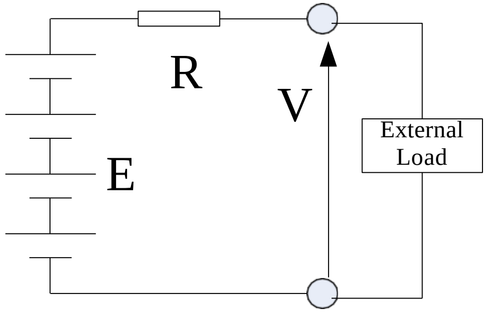
- Most of the disappointments connected with battery use, such as their limited life, self- discharge, reduced efficiency at higher currents.

Battery Parameters

- ***Cell and battery voltages***

Cells can be connected in series to give the overall voltage required. The ‘internal resistance’ and the equivalent circuit of a battery is shown in **Figure 1**. The battery is represented as having a fixed voltage *E*, but the voltage at the terminals is a different voltage *V* , because of the voltage across the internal resistance *R*

$$V = E - IR \qquad (1)$$



- ***Charge (or Ahr) capacity - E***lectric charge that a battery can supply

Most crucial parameter.. SI unit - Coulomb, the charge when one Amp flows for one second. The capacity of a battery might be, say, 10Amphours. This means it can provide 1Amp for 10 hours.

- ***Energy stored***

The energy stored in a battery depends on its *voltage*, and the *charge* stored. The SI unit is the Joule, but this is an inconveniently small unit, and so we use the Whr instead.

$$\text{Energy in Whr} = V * Ahr \qquad (2)$$

- ***Specific energy* - *A***mount of electrical energy stored for every kilogram of battery mass. It has units of $Wh.kg^{-1}$.
- ***Energy density* - *A***mount of electrical energy stored per cubic metre of battery volume. It normally has units of $Wh.m^{-3}$.
- ***Specific power* -*A***mount of power obtained per kilogram of battery.

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

- ***Ahr (or charge) efficiency***

In an ideal world a battery would return the entire charge put into it, in which case the amp hour efficiency is 100%. However, no battery does; its charging efficiency is less than 100%. The precise value will vary with different types of battery, temperature and rate of charge. It will also vary with the state of charge.

- ***Energy efficiency* - *R***atio of electrical energy supplied by a battery to the amount of electrical energy required to return it to the state before discharge.
- ***Self-discharge rates***

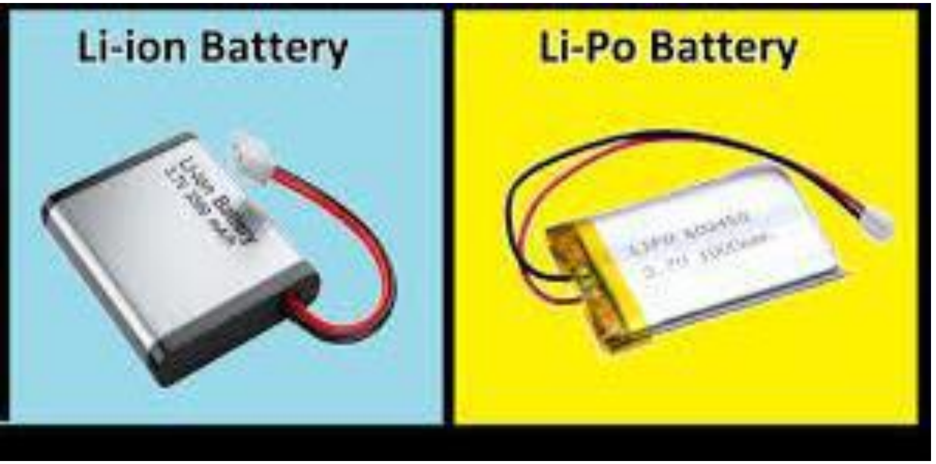
Most batteries discharge when left unused, and this is known as self-discharge. This is important as it means some batteries cannot be left for long periods without recharging. The rate varies with battery type, and with other factors such as temperature; higher temperatures greatly increase self-discharge.

- ***Depth of Discharge***: Depth of Discharge is defined as the capacity that is discharged from a fully charged battery, divided by battery nominal capacity.
- If a 100 A h battery is discharged for 20 minutes at a current of 50 A, the depth of discharge: ??

- ***State of charge (SoC)*** : level of charge of an electric battery relative to its capacity. The units of SoC are percentage points (0% = empty; 100% = full).
- DoD- inverse of SoC (100% = empty; 0% = full). SoC is normally used when discussing the current state of a battery in use, DoD is when discussing the lifetime of the battery after repeated use.

- ***Battery temperature, heating and cooling needs***

Most batteries run at ambient temperature, some run at higher temperatures and need heating to start with and then cooling when in use. In others, battery performance drops off at low temperatures, which is undesirable, but this problem could be overcome by heating the battery. When choosing a battery the designer needs to be aware of battery temperature, heating and cooling needs, and has to take these into consideration during the vehicle design process.

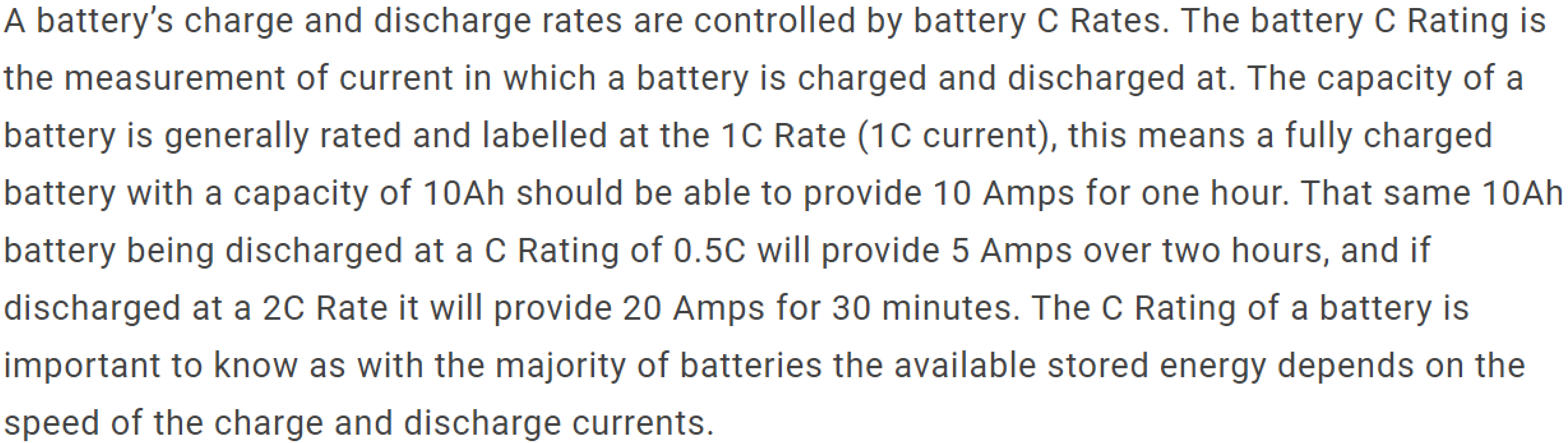


- Lead acid, nickel iron, nickel cadmium, nickel metal hydride, lithium polymer and lithium iron,

NASA G2 flywheel for spacecraft energy storage[edit]

This was a design funded by NASA's Glenn Research Center and intended for component testing in a laboratory environment. It used a carbon fiber rim with a titanium hub designed to spin at 60,000 rpm, mounted on magnetic bearings. Weight was limited to 250 pounds. Storage was 525 W-hr (1.89 MJ) and could be charged or discharged at 1 kW.[36] The working model shown in the photograph at the top of the page ran at 41,000 rpm on September 2, 2004

C Rating of Battery:



A battery’s charge and discharge rates are controlled by battery C Rates. The battery C Rating is the measurement of current in which a battery is charged and discharged at. The capacity of a battery is generally rated and labelled at the 1C Rate (1C current), this means a fully charged battery with a capacity of 10Ah should be able to provide 10 Amps for one hour. That same 10Ah battery being discharged at a C Rating of 0.5C will provide 5 Amps over two hours, and if discharged at a 2C Rate it will provide 20 Amps for 30 minutes. The C Rating of a battery is important to know as with the majority of batteries the available stored energy depends on the speed of the charge and discharge currents.

VEHICLES ENERGY CONSUMPTION

Energy required = Volts x (Amp Draw / km) , kWh/km

Two wheelers : 50 - 100 Wh/km

Car : 150 - 250 Wh/km

Medium Commercial Vehicle : 300 - 400 Wh/km

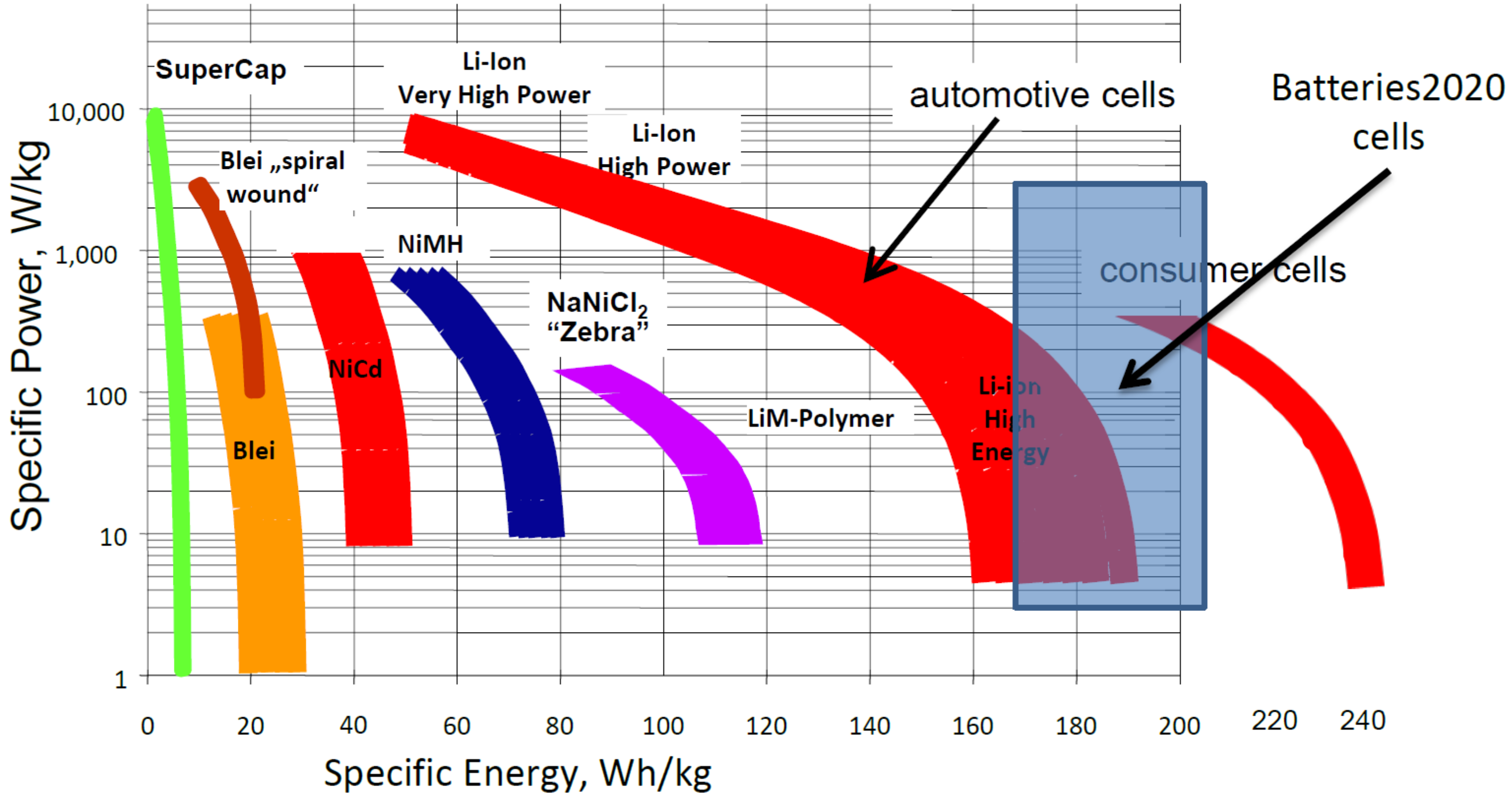
Range of vehicle depends on mainly energy consumption in addition to speed, pack kWh rating, driving conditions, hills, aerodynamics, vehicle weight, temperature, driving styles and several other factors.

Distance = (kWh of pack / Wh/km), km

BATTERY TERMINOLOGIES (Cont'd)

➢Specific Power

Measure of discharge power available from a battery pack per unit weight (W/kg)



Source: Saft

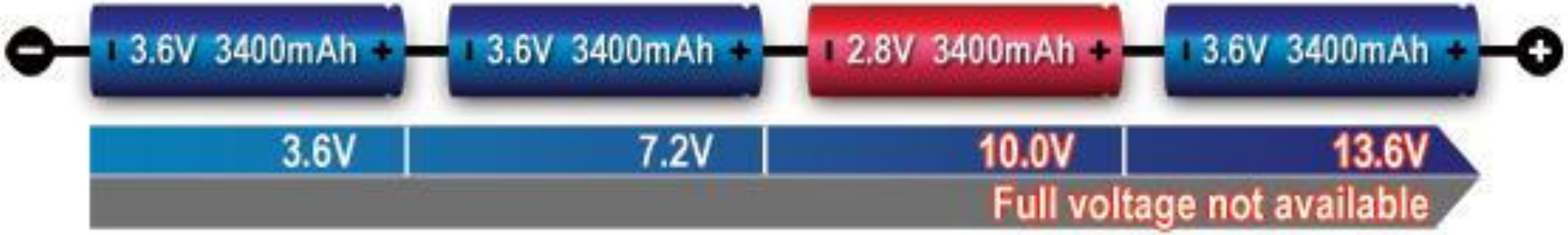
Li-Ion battery has comparable specific power of lead acid battery (250-600 W/kg)

COMPARISON OF BATTERIES

Properties	Lead Acid	Nickel-Cadmium	Nickel-Metal Hydride	Li-Ion
Specific Energy (Wh/kg)	30 – 40	40 – 60	40 – 80	130 – 200
Energy Density (Wh/L)	60 – 90	80 – 140	90 – 160	180 – 320
Specific Power (W/kg)	250 – 600	300 – 800	900 – 1600	1200 – 4000
Charge/Discharge Efficiency (%)	75 – 90	75 – 93	80 – 95	85 – 96
Self-discharge Rate (per month)	5 – 15	5 – 15	8 – 15	< 5
Cycle Durability (cycles)	500 – 800	800 – 1200	800 – 1200	1500 – 2000
Nominal Cell Voltage (V)	~ 2.1	~ 1.2	~1.2	~ 3.75

CELLS IN SERIES

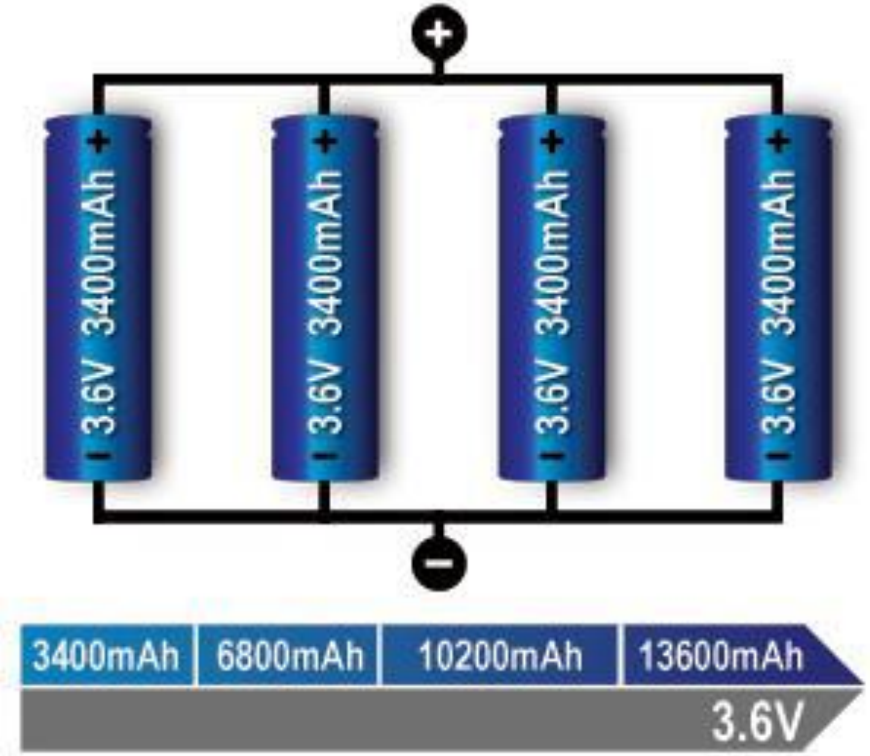
Proper Cells



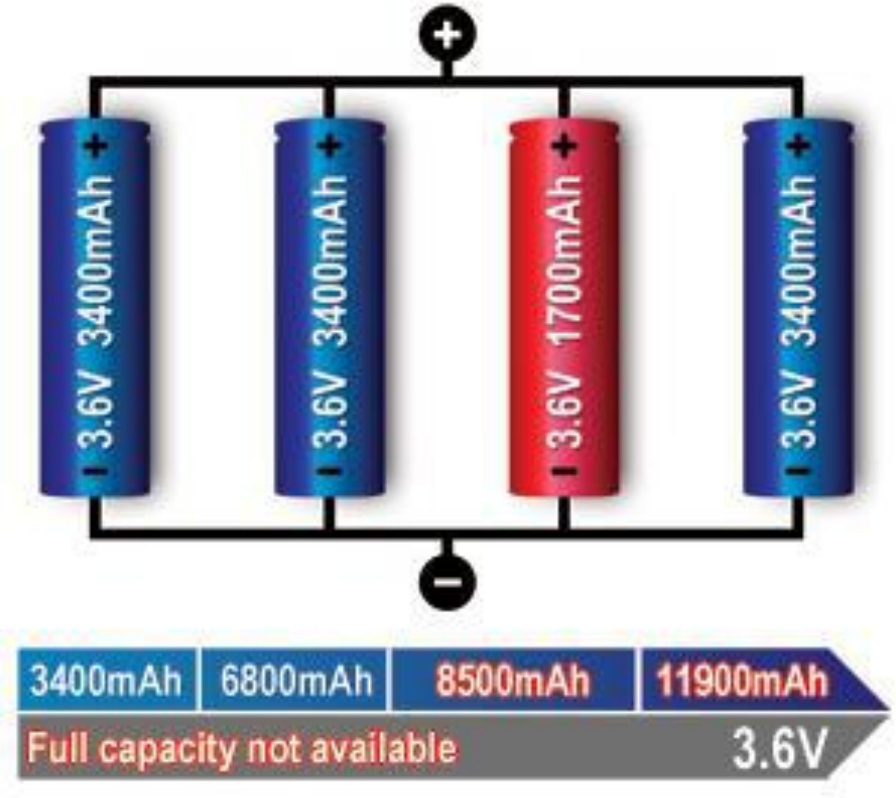
Faulty Cell

Source : Battery University

CELLS IN PARALLEL



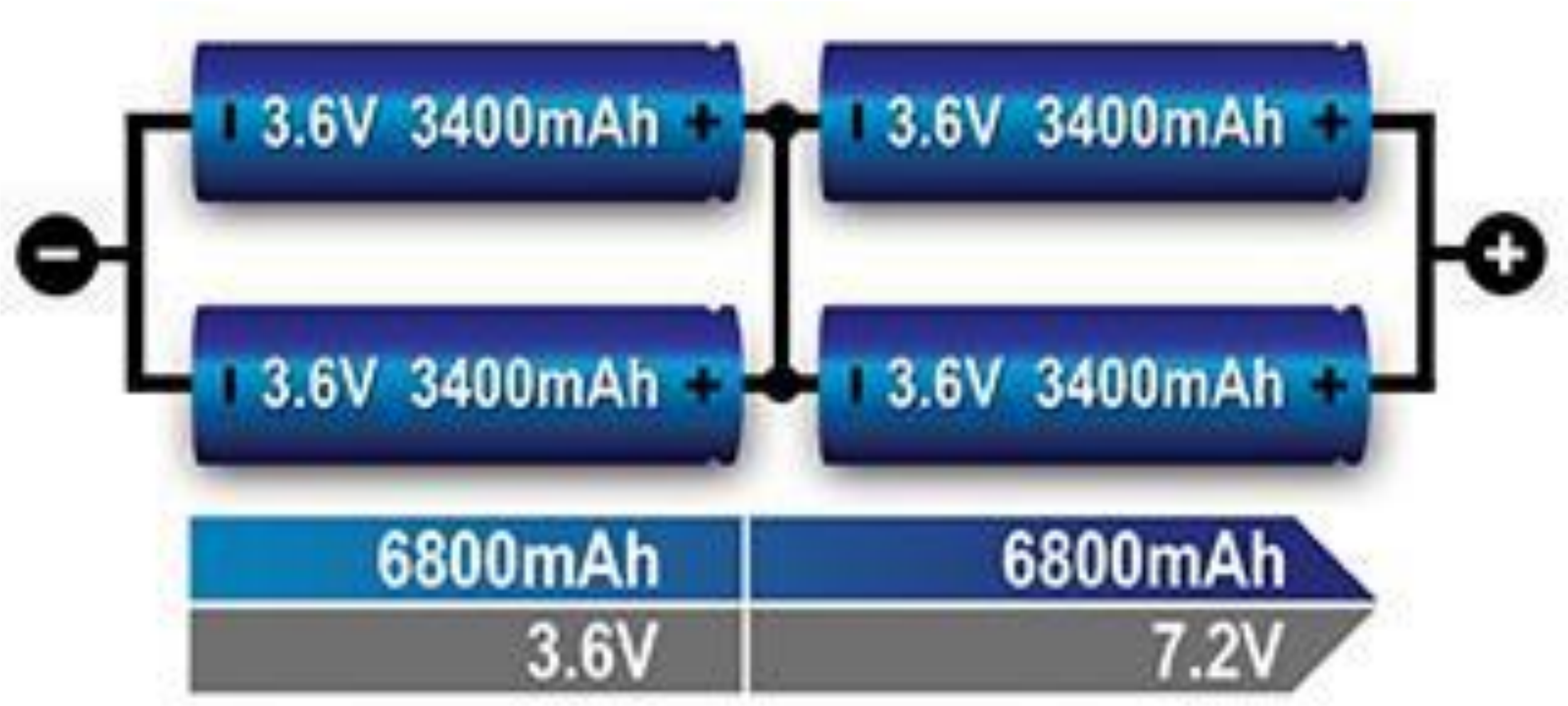
Proper Cells



Faulty Cells

Source : Battery University

CELLS IN SERIES - PARALLEL

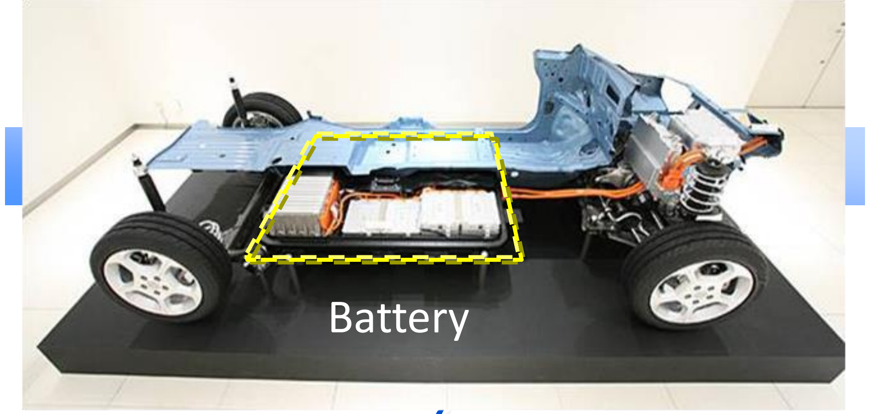


Tesla has 85 kWh battery with 7104 cells with 96 cells in series and 74 cells in parallel (96s74p)

Source : Battery University

NISSAN LEAF VEHICLE STRUCTURE

Chassis



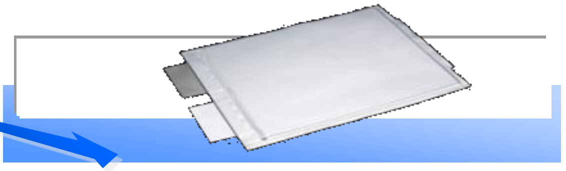
E

Battery Management System
Junction Box
Service Disconnect Switch Etc

Module

48 modules / vehicle

Cell



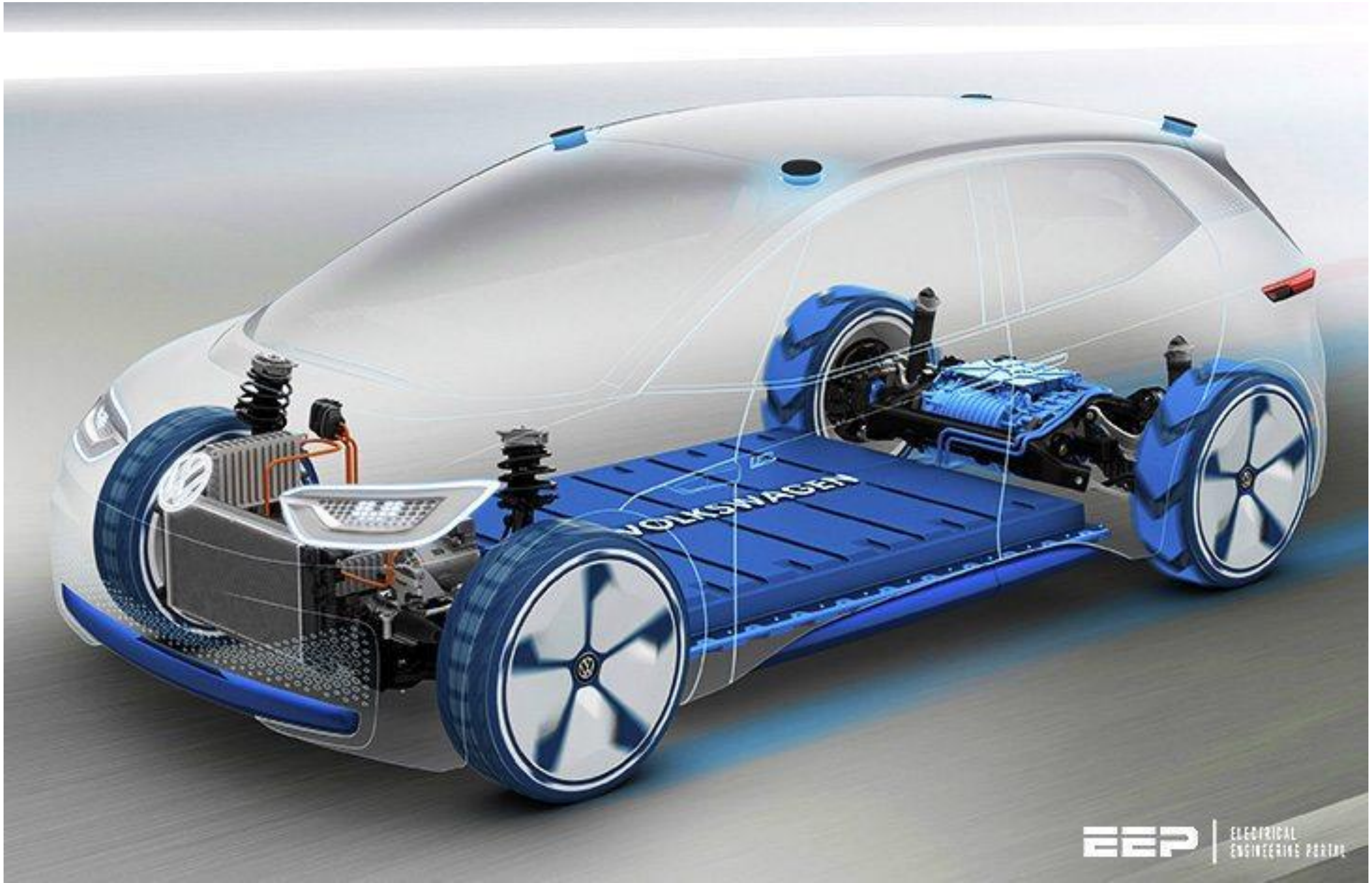
192 cells / vehicle
4 cells / module

Source : Nissan

BATTERY PACK OF CHEVY BOLT

Source : Battery University

BATTERY PACK ON VOLKSWAGON



ELECTRIC VEHICLES DETAILS

EV MAKE	BATTERY (kWh)	RANGE (km)	Wh / km
BMW i3 (2019)	42	345	165
GM Spark	21	120	175
Honda Fit	20	112	180
Nissan Leaf	30	160	190
Mitsubishi MiEV	16	85	190
Ford Focus	23	110	200
Bercedes B	28	136	205
Tesla 3	75	496	151

Source : Battery University

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- commercial availability
- self-discharge rates
- recharge rates

* energy density
* typical voltages
* energy efficiency
* cost, operating temperatures
* number of life cycles

How energy availability varies with regard to:

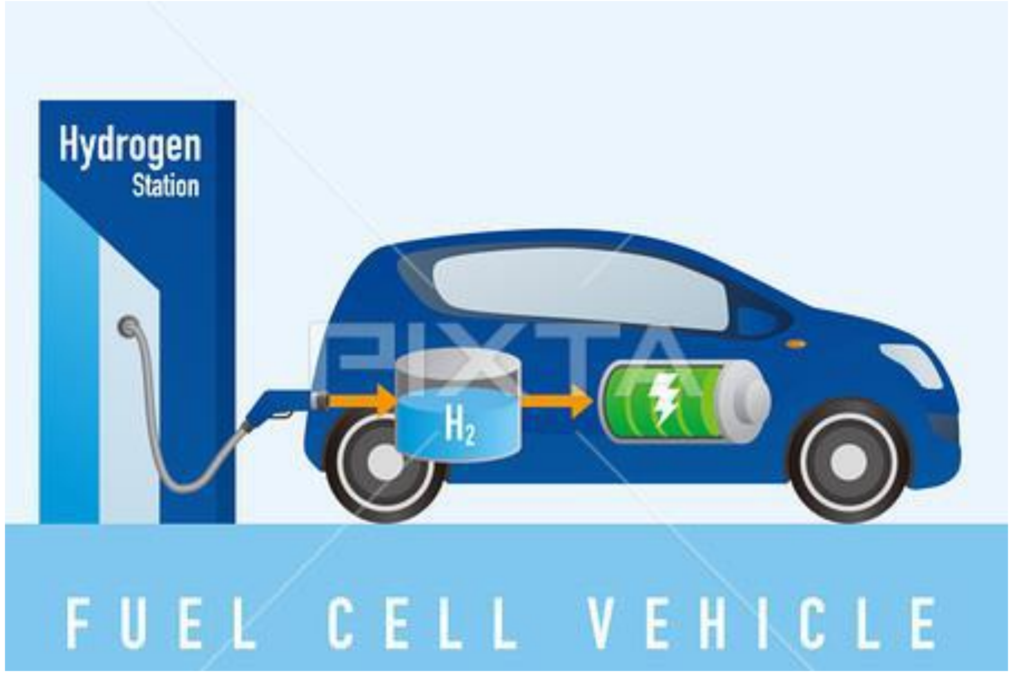
- ambient temperature
- battery geometry
- charging methods

* charge and discharge rates
* optimum temperature
* cooling needs.

- Most of the disappointments connected with battery use, such as their limited life, self- discharge, reduced efficiency at higher currents.

Fuel Cell

- Fuel cell
- Issues in fuel cell
- Hydrogen fuel cell
- Main reasons for loss in voltage



Fuel Cell

Introduction

- Fuel cells were invented in about 1840, but they are yet to really make their mark as a power source for electric vehicles.
- This might be set to change over the next 20 or 30 years.
- Most of the major motor companies are spending very large sums of money developing fuel cell powered vehicles.
- Basic principle of the fuel cell is that it uses hydrogen fuel to produce electricity . The basic chemical reaction is:

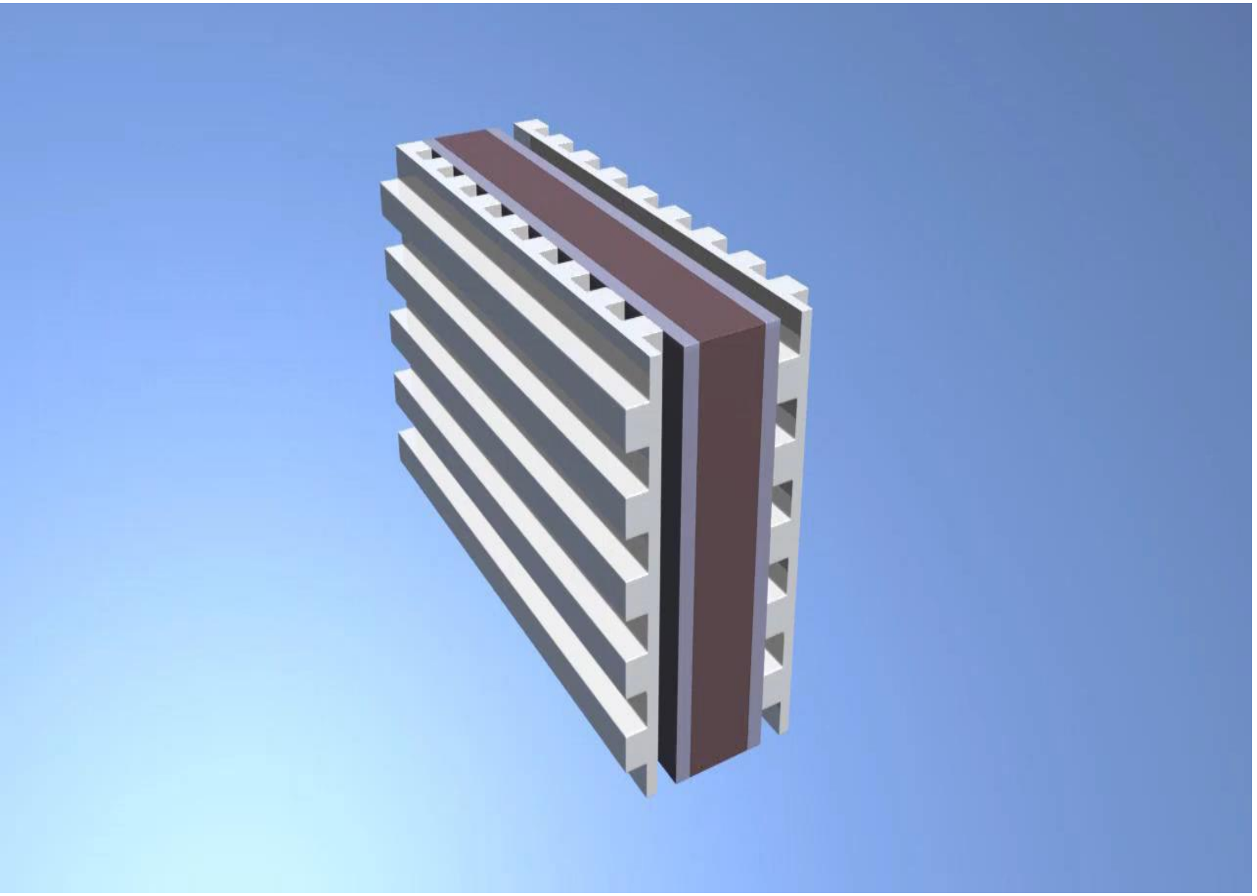
$$2H_2 + O_2 = 2H_2O \qquad (1)$$

- The product is thus water, and energy.
- Fuel cell likely to be used in vehicles work at quite modest temperatures (~85°C) there is no nitrous oxide produced by reactions between the components of the air used in the cell. A fuel cell vehicle could thus be described as ***zero-emission vehicle*** with a range and performance broadly comparable with IC engine vehicles.

Fuel Cell

- Fuel cells work like batteries, but they *do not need recharging*. They produce electricity and heat as long as fuel is supplied.
- A fuel cell consists of two electrodes—a negative electrode (or cathode) and a positive electrode (or anode)—sandwiched around an electrolyte.
- A fuel, such as hydrogen, is fed to the anode, and air is fed to the cathode. In a hydrogen fuel cell, a catalyst at the anode separates hydrogen molecules into protons and electrons, which take different paths to the cathode.
- The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they unite with oxygen and the electrons to produce water and heat.

Fuel Cell



Advantages of fuel cell:

- High Efficiency- when utilizing co-generation, fuel cells can attain over 80% energy efficiency
- Good reliability- quality of power provided does not degrade over time.
- Noise- offers a much more silent and smooth alternative to conventiona production.
- Environmentally beneficial- greatly reduces CO2 and harmful pollutant
- Size reduction- fuel cells are significantly lighter and more compact

Main issues in the fuel cell

There are many problems and challenges for fuel cells to overcome before they become a commercial reality as a vehicle power source. The main problems centre on the following issues.

- ***Cost:*** Fuel cells are currently far more expensive than IC engines, and even hybrid IC/electric systems.
- *Water management:* It is not at all self-evident why water management should be such an important and difficult issue with automotive fuel cells.
- ***Cooling:*** The thermal management of fuel cells is actually rather more difficult than for IC engines.
- ***Hydrogen supply:*** Hydrogen is the preferred fuel for fuel cells, but hydrogen is very difficult to store and transport. There is also the vital question of 'where does the hydrogen come from' these issues are so difficult and important, with so many rival solutions.
- There is great hope that these problems can be overcome, and fuel cells can be the basis of less environmentally damaging transport.

Hydrogen Fuel Cells: Basic Principles

Electrode reactions

Basic principle of the fuel cell is the release of energy following a chemical reaction between hydrogen and oxygen. The key difference between this and simply burning the gas is that the energy is released as an electric current, rather that heat. How is this electric current produced?

- At the anode of an acid electrolyte fuel cell the hydrogen gas ionizes, releasing electrons and creating H^+ ions (or protons).

$$2H_2 \rightarrow 4H^+ + 4e^-$$

Cathode Reaction:

Oxygen reacts with electrons taken from the electrode, and H+ ions from the electrolyte, to form water.

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O$$

Electrons produced at the anode must pass through an electrical circuit to the cathode. Also, H^+ ions must pass through the electrolyte. An acid is a fluid with free H^+ ions, and so serves this purpose very well. Certain polymers can also be made to contain mobile H^+ ions.

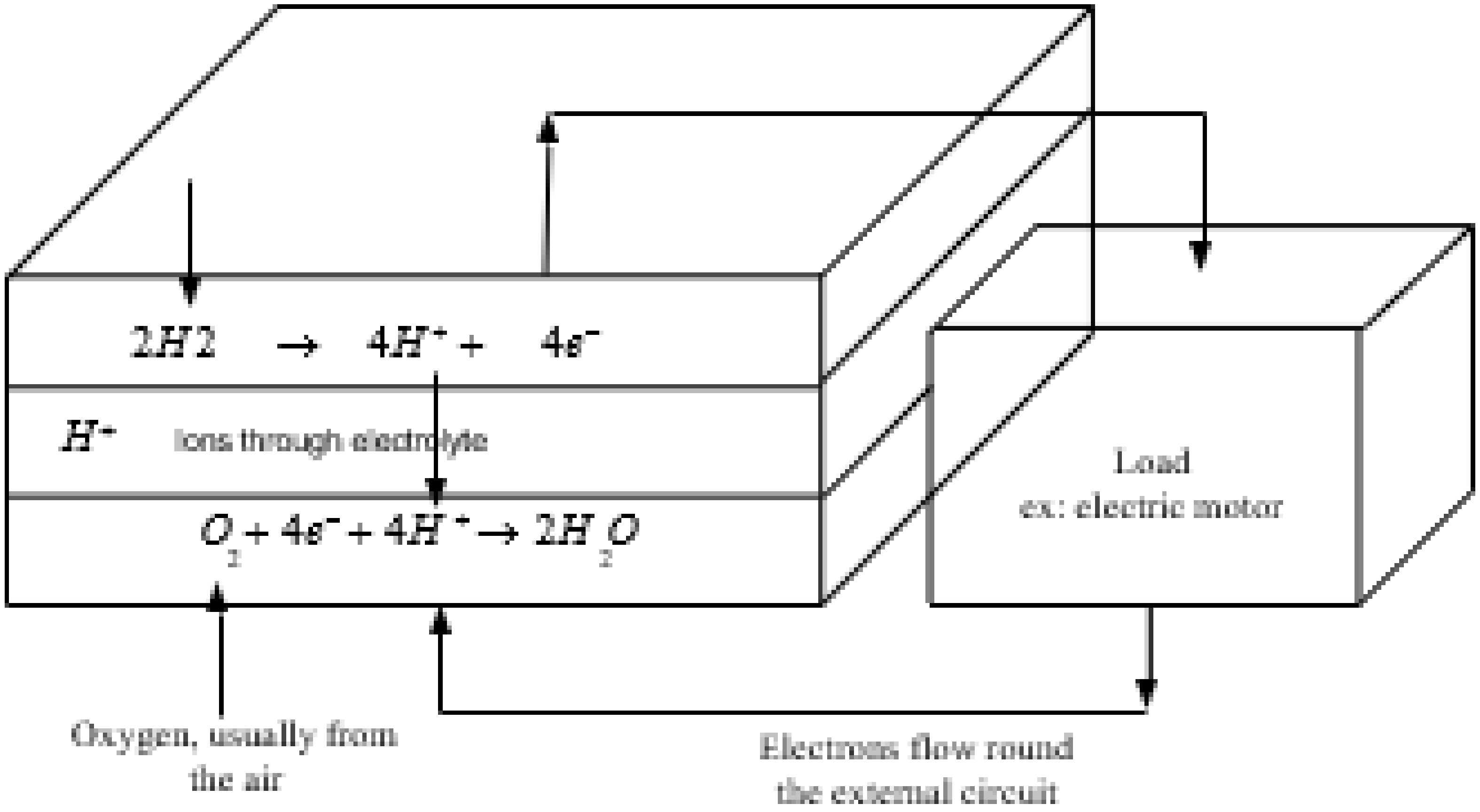
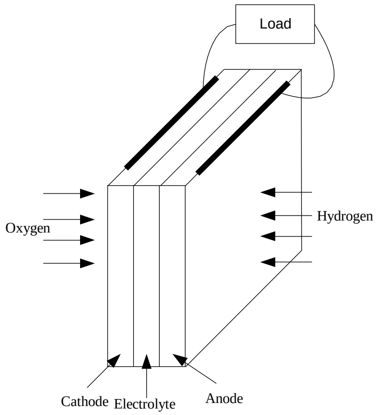


Fig. 1 The reactions at the electrodes, and the electron movement, in a fuel cell with an acid Electrolyte

Fig. 2 is another representation of a fuel cell. Hydrogen is fed to one electrode, and oxygen, usually as air, to the other. A load is connected between the two electrodes, and current flows.

The three main ways of dealing with the slow reaction rates are: the use of suitable catalysts on the electrode, raising the temperature, and increasing the electrode area.

The structure of the electrode is also important. It is made highly porous so that the real surface area is much greater than the normal length × width. As well as being of a large surface area, and highly porous, a fuel cell electrode must also be coated with a catalyst layer. In the case of the PEMFC this is platinum, which is highly expensive. The catalyst thus needs to be spread out as finely as possible. This is normally done by supporting very fine particles of the catalyst on carbon particles.



SUPERCAPACITOR:

- Ultracapacitor, a supercapacitor – like a battery
- It is a means to store and release electricity. But rather than storing energy in the form of chemicals, supercapacitors store electricity in a **static state**, making them better at rapidly charging and discharging energy.

Lithium-ion batteries work by using layers of cells with using positive and negative electrodes separated by an electrolyte. They generate a charge as lithium ions move from negative to positive when discharging, and the reverse happens when charging.
How do supercapacitors work?

Capacitors, on the other hand, store electricity in a static state, rather than leaving it 'locked up' in chemical reactions.

- Electrodes, separated by an insulating material known as a dielectric. These two plates, one positive and the other negative, generate an electrical field when connected to an electric circuit, which polarizes the atoms in the dielectric so the positive atoms sit on the side of the negative plate and negative atoms on the side of a positive plate, thus creating a charge.

- Supercapacitor is simply a larger capacitor with bigger electrode plates and less distance between them, allowing for a greater charge to be stored in the form of electrical potential energy.
- A supercapacitor doesn't use a dielectric; instead porous electrode plates are soaked in an electrolyte and separated by a very thin separator material. When a charge is passed through the electrodes, the atoms in them become polarized - giving the electrodes a positive or negative charge.
- These then attract electrons of the opposite polarity in the electrolyte, and thus create a double electric layer, meaning supercapacitors store a lot more power than their regular capacitor counterparts.

Advantages of supercapacitors:

- Supercapacitors already exist in cars with regenerative braking systems. This is thanks to their greater power density than chemical reaction-based batteries, which allows them to rapidly store and discharge electricity, handy for collecting energy generated under braking then quickly releasing it upon acceleration.
- Full cell-based cars, like the Toyota FCHV, also use supercapacitors to deliver auxiliary accelerative power that hydrogen fuel-cells struggle to do alone.
- They've yet to take over from lithium-ion batteries as the primary power source, but electric and hybrid vehicles are advancing year on year, so there's a lot of potential for supercapacitors to play a bigger role in next-generation electric cars and charging infrastructure to support them.
- As supercapacitors pretty much rely on physics rather than chemistry to store their energy, they don't degrade in the same fashion as lithium-ion batteries. That could present a huge opportunity in improving the lifespan of an electric car, as well as reducing the environmental impact of using lithium-ion power cells.

But the largest advantage of supercapacitors over lithium-ion and nickel cadmium batteries is their ***ability to charge and discharge rapidly.***

Disadvantages of supercapacitors:

- Supercapacitors can absorb and deliver a large amount of power, faster than lithium-ion batteries – but right now, they **aren't able to store** as much.
- The second issue with supercapacitors as they stand is discharging, or the ***amount of time*** they're able to hold a charge for. Currently, supercapacitors can't hold a charge as long as a lithium-ion battery. If you left a supercapacitor-powered car in the garage for a week, for example, you'd likely find it with no charge when you returned.
- While supercapacitors may not be seen in EVs for a while, the technology already fits perfectly into hybrid powertrains. Supercapacitors are already used to rapidly charge the power supplies in hybrid buses as they go from stop to stop – but car makers such as Lamborghini are finding they can also add some serious extra performance, too.

When hybrid energy is used purely for performance, issues such as range and the ability to hold charge aren't as important – and that's why we're already seeing the technology creep into the hypercar world.

The Lamborghini Sian combines a supercapacitor-powered 34bhp e-motor in conjunction with a Sant'Agata V12, for sub 3.0sec 0-62mph performance.

ENERGY STORAGE : Batteries

- ***Battery*** : two or more electric cells joined together.
- Cells convert ***chemical*** energy to ***electrical*** energy. Cells consist of positive and negative electrodes joined by an electrolyte. Chemical reaction between electrodes and electrolyte which generates DC electricity.
- In secondary or rechargeable batteries, the chemical reaction can be reversed by reversing the current and the battery returned to a charged state.
- ‘Lead acid’ battery is the most well known rechargeable type, but there are others.
- Lead acid, nickel iron, nickel cadmium, nickel metal hydride, lithium polymer and lithium iron, sodium sulphur and sodium metal chloride.
  - Battery Parameters
  - Lead acid batteries
  - Lithium ion batteries
  - Metal air batteries
  - Battery Charging

Overview of Batteries

Battery can be treated as a ‘black box’ which has a range of performance criteria. These criteria will include:

- specific energy
- specific power
- amp hour efficiency
- commercial availability
- self-discharge rates
- recharge rates

* energy density
* typical voltages
* energy efficiency
* cost, operating temperatures
* number of life cycles

How energy availability varies with regard to:

- ambient temperature
- battery geometry
- charging methods

* charge and discharge rates
* optimum temperature
* cooling needs.

- Most of the disappointments connected with battery use, such as their limited life, self- discharge, reduced efficiency at higher currents.

SUPERCAPACITOR:

- **Ultracapacitor** Or Supercapacitor – like a battery
- It is a means to store and release electricity. But rather than storing energy in the form of chemicals, supercapacitors store electricity in a **static state**, making them better at rapidly charging and discharging energy.
- Supercapacitors have several benefits over batteries
  - ► But currently a few drawbacks too
  - ► They're used in the new ***Lamborghini Sian***

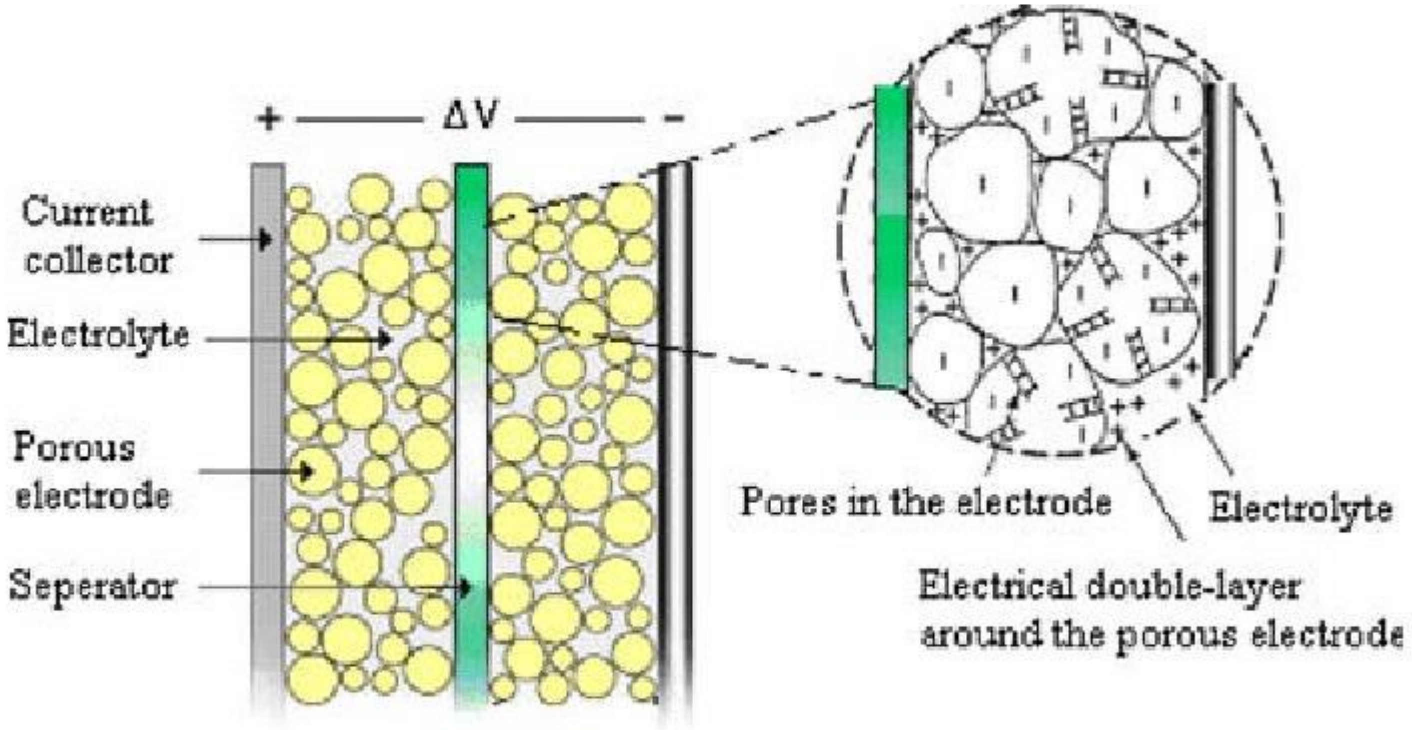
SUPERCAPACITOR:

How do supercapacitors work?

- Electrodes, separated by an insulating material known as a dielectric. These two plates, one positive and the other negative, generate an electrical field when connected to an electric circuit, which polarizes the atoms in the dielectric so the positive atoms sit on the side of the negative plate and negative atoms on the side of a positive plate, thus creating a charge.

SUPERCAPACITOR:

- Supercapacitor is a larger capacitor with bigger electrode plates and less distance between them, allowing for a greater charge to be stored in the form of electrical potential energy.
- A supercapacitor doesn't use a dielectric; instead porous electrode plates are soaked in an electrolyte and separated by a very thin separator material. When a charge is passed through the electrodes, the atoms in them become polarized - giving the electrodes a positive or negative charge.
- These then attract electrons of the opposite polarity in the electrolyte, and thus create a double electric layer, meaning supercapacitors store a lot more power than their regular capacitor counterparts.
- ***High value of Specific Power***
- ***Double layer Capacitor***



Individual Supercapacitor Cell

10.2.2 Basic Principles of Ultracapacitors

Double-layer capacitor technology is the major approach to achieving the ultracapacitor concept. The basic principle of a double-layer capacitor is illustrated in Figure 10.8. When two carbon rods are immersed in a thin sulfuric acid solution, separated from each other and charged with voltage increasing from zero to 1.5 V, almost nothing happens up to 1 V; then at a little over 1.2 V, a small bubble will appear on the surface of both the electrodes. Those bubbles at a voltage above 1 V indicate electrical decomposition of water. Below the decomposition voltage, while the current does not flow, an "electric double layer" then occurs at the boundary of electrode and electrolyte. The electrons are charged across the double layer and for a capacitor.

An electrical double layer works as an insulator only below the decomposing voltage. The stored energy, E_{cap}, is expressed as

$$E_{cap} = \frac{1}{2}CV^2, \tag{10.22}$$

where C is the capacitance in Faraday and V is the usable voltage in volt. This equation indicates that the higher rated voltage V is desirable for larger energy density capacitors. Up to now, capacitors' rated voltage with an aqueous electrolyte has been about 0.9 V per cell, and 2.3 to 3.3 V for each cell with a nonaqueous electrolyte.

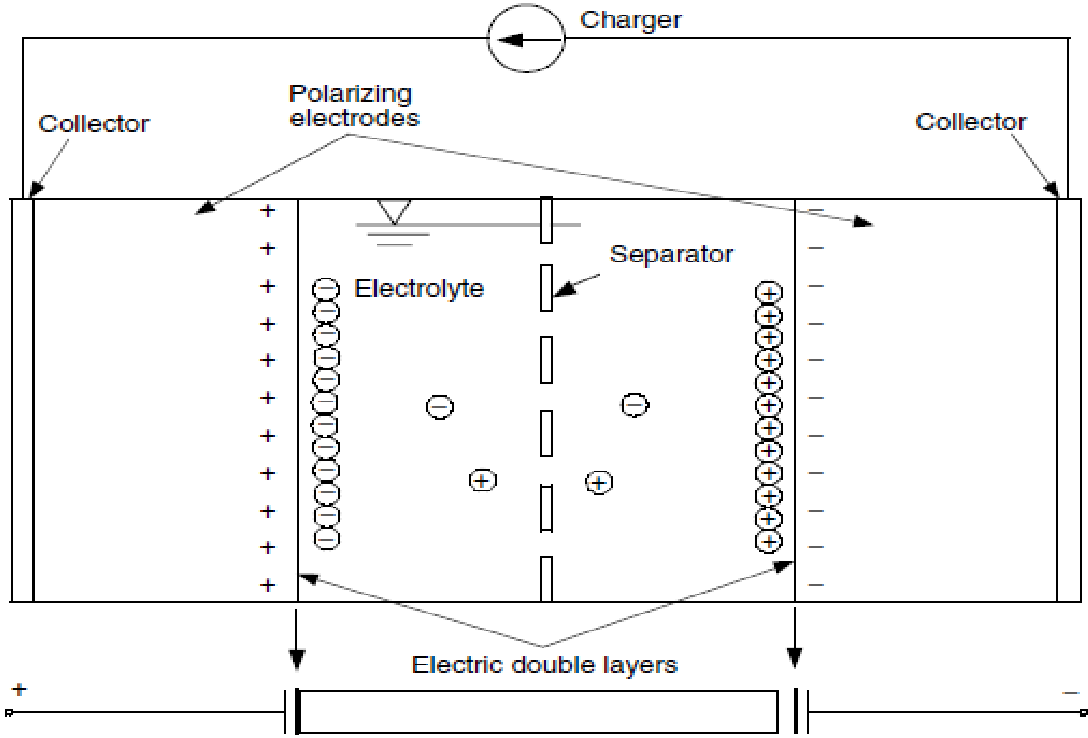


FIGURE 10.8
Basic principles of a typical electric double-layer capacitor

Advantages of Supercapacitors:

- Supercapacitors already exist in cars with regenerative braking systems. This is thanks to their greater power density than chemical reaction-based batteries, which allows them to rapidly store and discharge electricity, handy for collecting energy generated under braking then quickly releasing it upon acceleration.
- Full cell-based cars, like the Toyota FCHV, also use supercapacitors to deliver auxiliary accelerative power that hydrogen fuel-cells struggle to do alone.
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- Low Specific Energy
- While supercapacitors may not be seen in EVs for a while, the technology already fits perfectly into hybrid powertrains. Supercapacitors are already used to rapidly charge the power supplies in hybrid buses as they go from stop to stop – but car makers such as Lamborghini are finding they can also add some serious extra performance, too.

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Hybridization of Energy Sources:

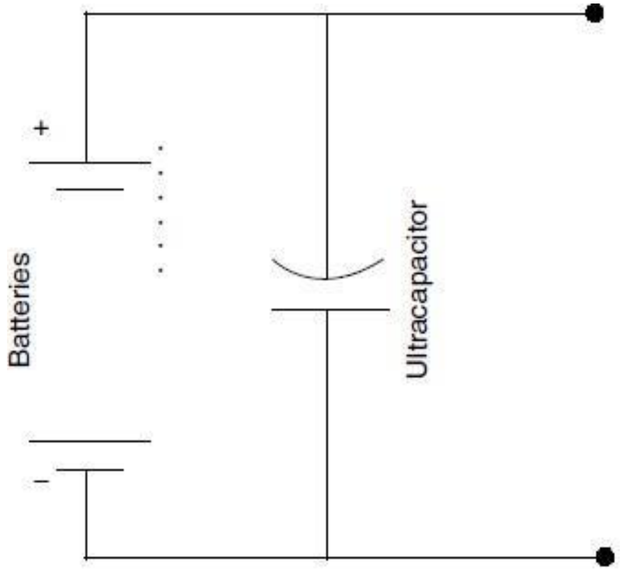
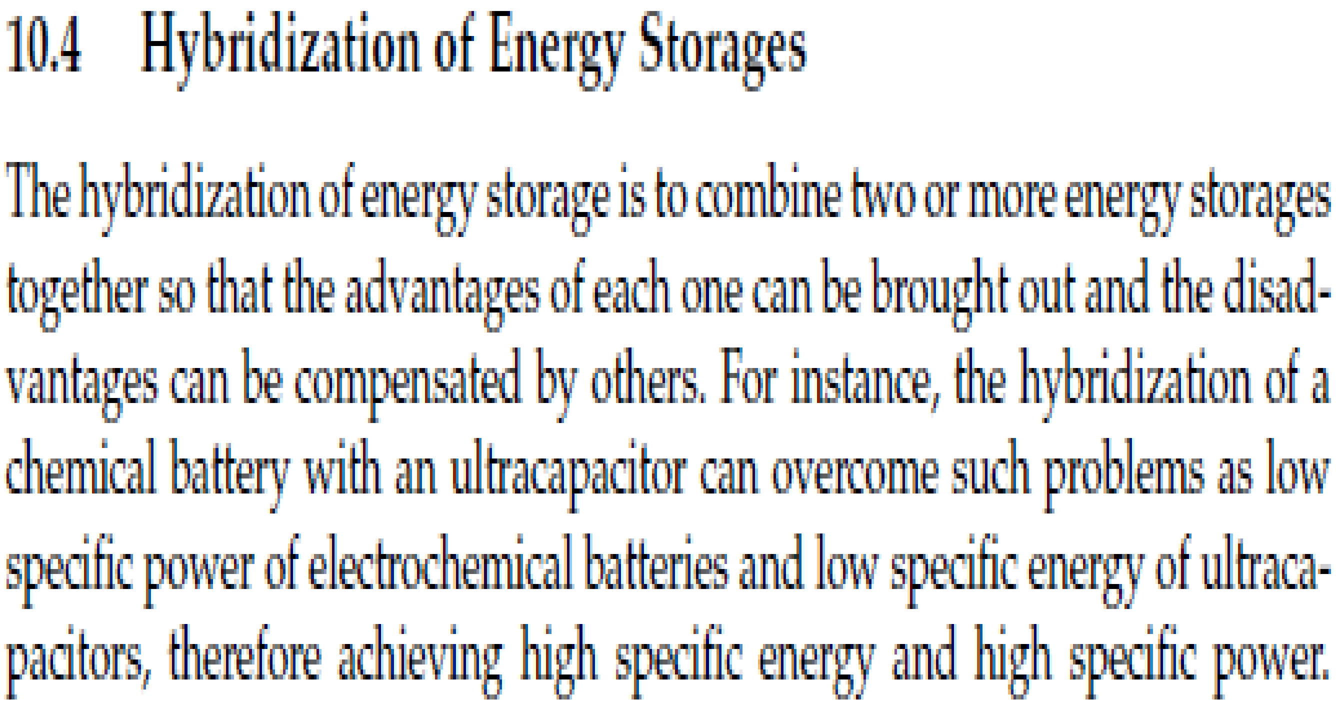


FIGURE 10.19
Direct and parallel connection of batteries and ultracapacitors



10.4 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.

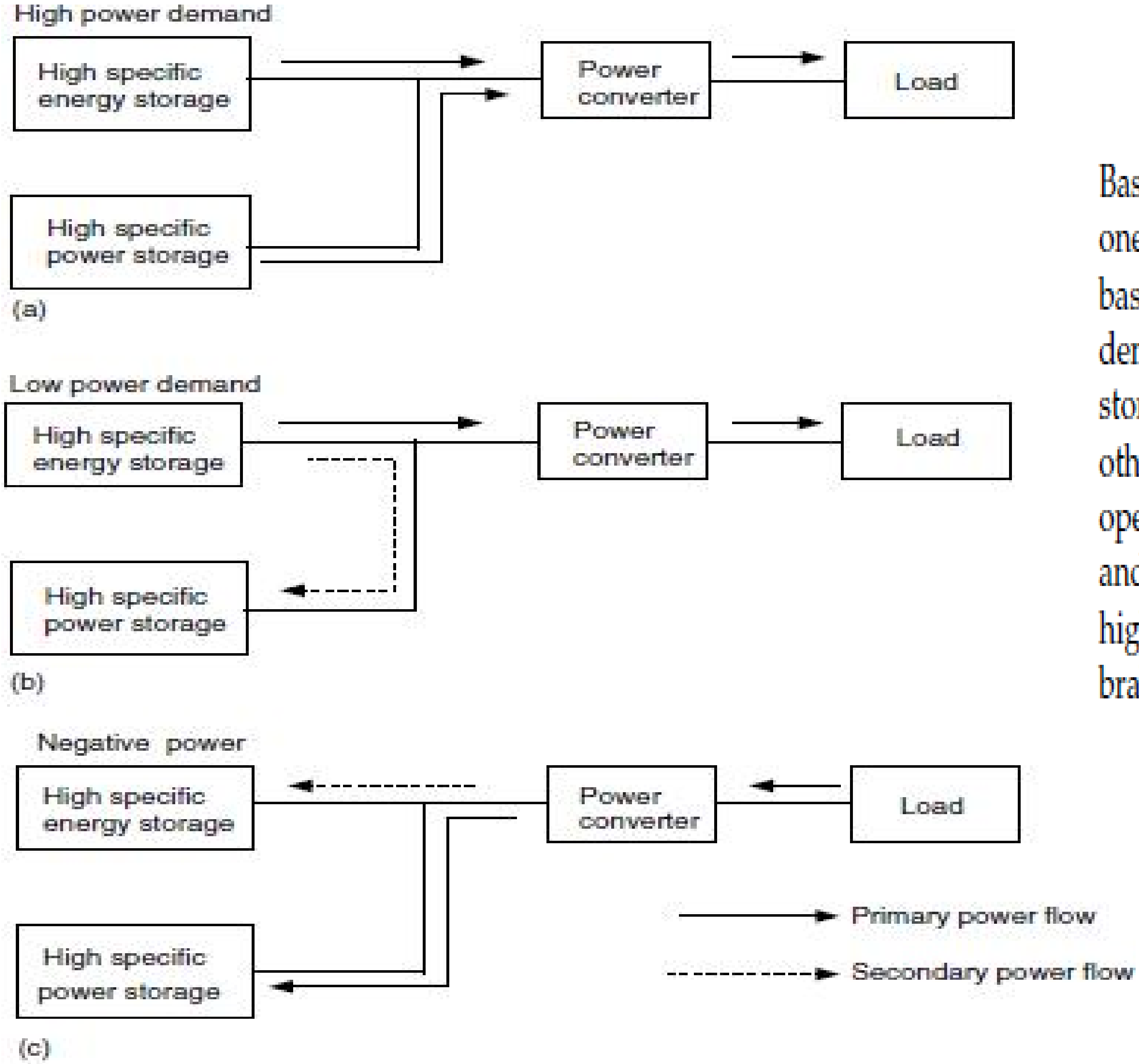


FIGURE 10.18
Concept of a hybrid energy storage operation

Basically, the hybridized energy storage consists of two basic energy storages: one with high specific energy and the other with high specific power. The basic operation of this system is illustrated in Figure 10.18. 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 10.18(a). 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

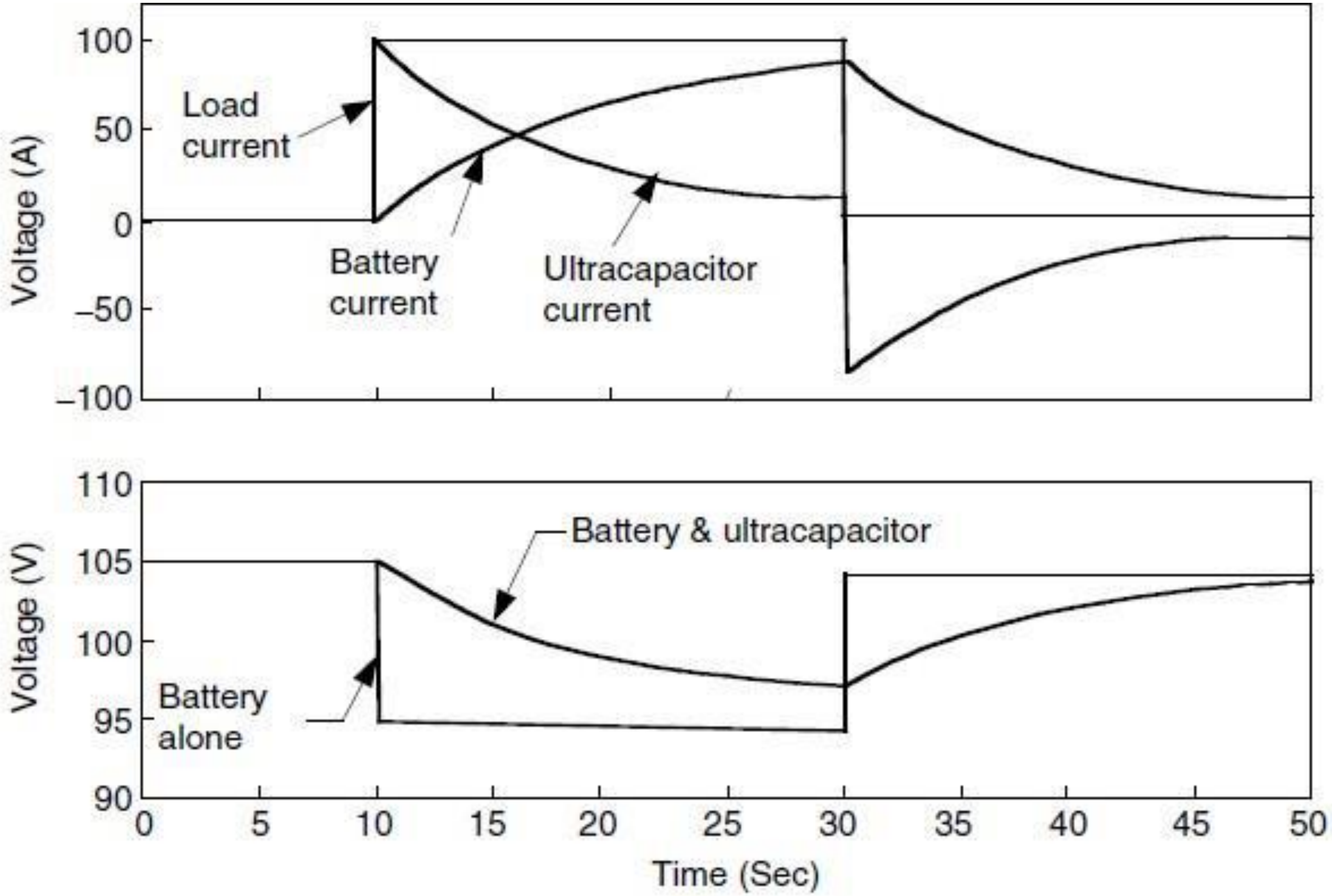


FIGURE 10.20
Variation of battery and ultracapacitor currents and voltages with a step current output change

Tesla CyberTruck

- Chinese startup EdisonFuture recently unveiled a solar and electric truck.

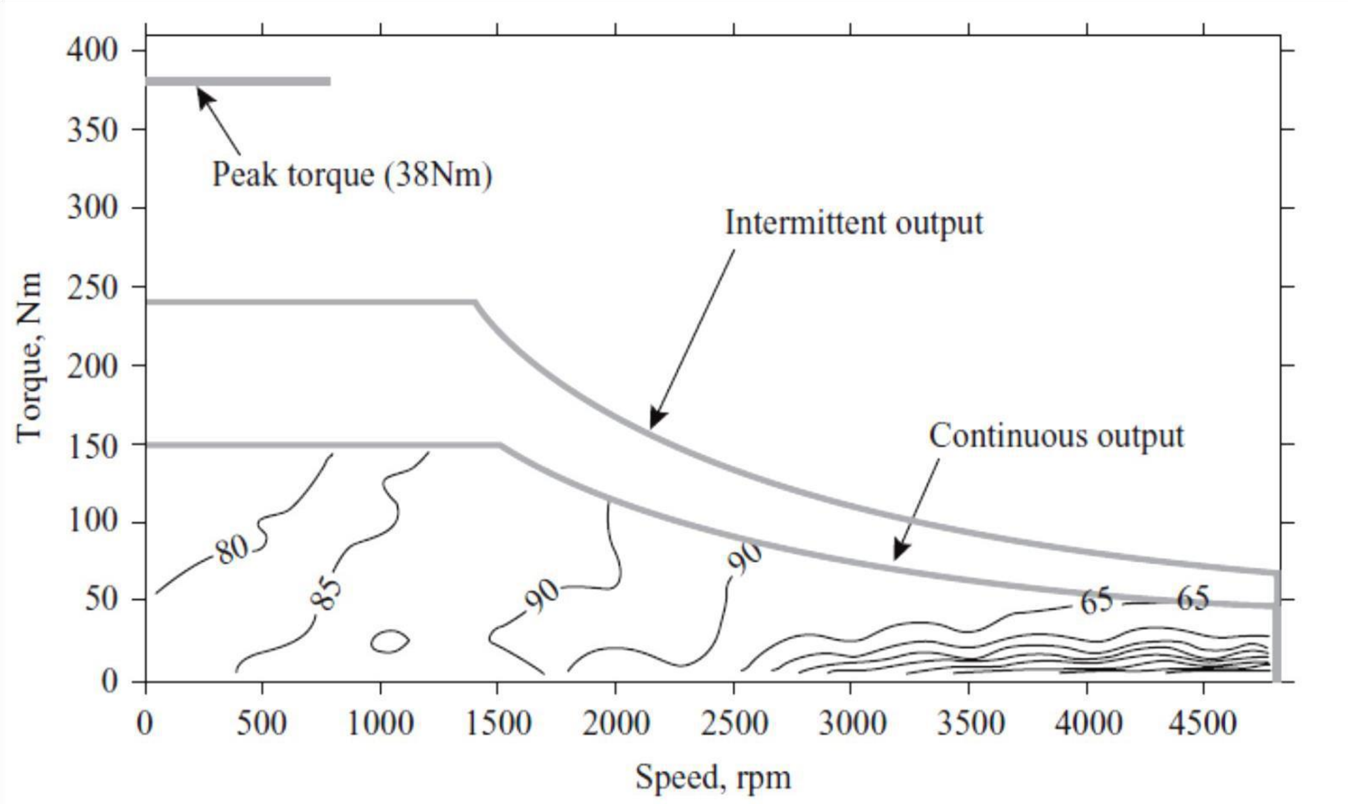
Sizing the propulsion motor

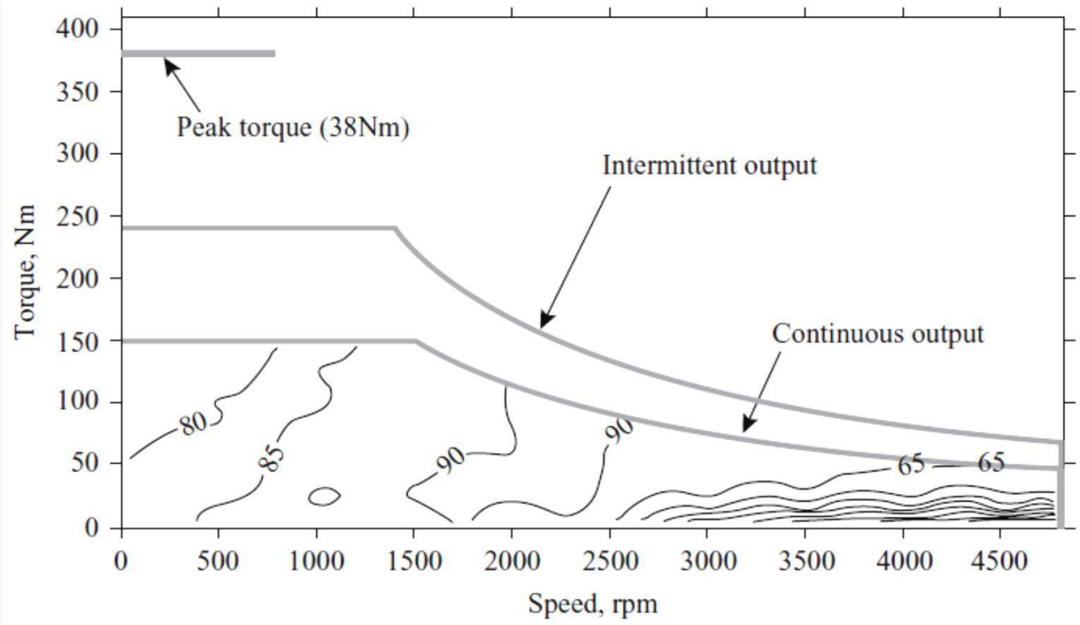
- An electric machine is at the core of hybrid propulsion
- The motor-generator M/G : ***maximum input speed at transmission is restricted to <12 000 rpm*** from the engine side and on the transmission side by the proper gear selection.
- M/G torque and power is customised by the ***electric fraction***, *EF*, defined as the ratio of M/G peak power to total peak power. For virtually all hybrid propulsion systems this fraction ranges from **0.1< EF < 0.4.**

For the sizing of propulsion motor the following discussions are needed,

1. *Torque and power*

- Torque and power define the peak operating capability of the hybrid electric system.
- Capability curve defines the operating bounds of the hybrid ac drive system. Figure shows the defining characteristics of the torque-speed:





i. ***Continuous rating***: The EM can be operated whin its continuous rated region.

ii. ***Intermittent overload operation***: The EM can operate in this regime for short duration (typically <30s).

iii. ***Peak overload operation***: The EM can operate in this region for a very short duration (typically <1~2s).

From **Figure 2** it can be seen that:

i. the peak output is about 2.5 times the continuous or rated output

ii. the intermittent output is about 1.5 times the continuous or rated output

The various operating regions show in **Figure 2** is:

i. the region the flat torque region is known as the ***constant torque operating region***. In this region the DC-AC converter has sufficient voltage from the dc sources to inject required current into the EM.

ii. when the machine speed increases and reaches the point **A**, the induced emf in the stator winding increases and the EM enters the constant power regime and flux weakening control is used.

Constant Power Speed Ratio (CPSR)

In **Figure 3** the operation of EM in different modes is shown. The description of various operation modes is as follows:

1. In the 1st quadrant the EM works as a motor and its direction of rotation is clockwise (CW).
2. In the 2nd quadrant, the EM operates as a generator and its direction of counter clockwise (CCW)
3. In 3rd quadrant the EM operates as motor and its direction of rotation is CCW
4. In the 4th quadrant the EM operates as a generator and its direction of rotation is CW

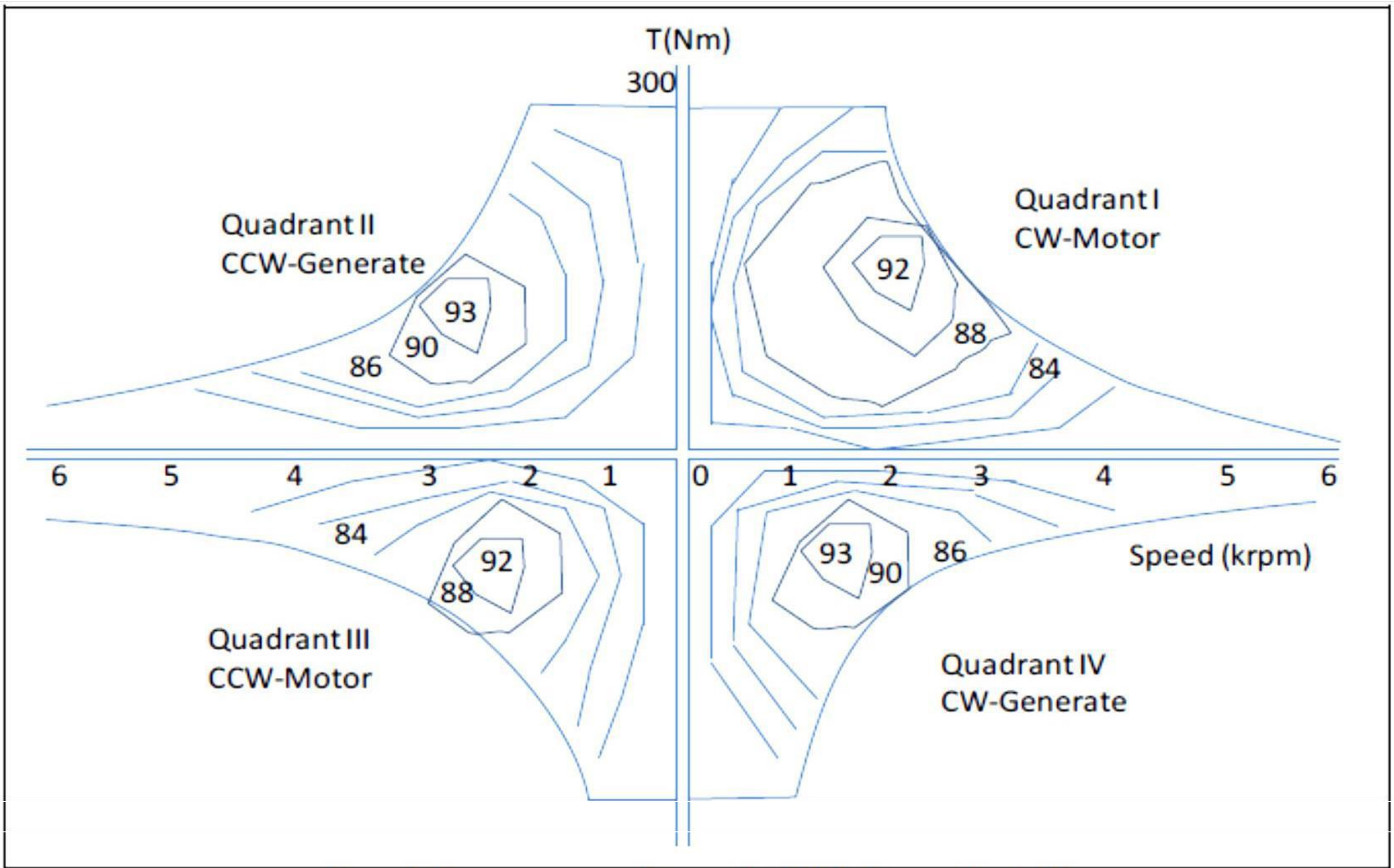


Figure 3: Torque versus speed curve of an EM for four quadrants [2]

With modern power electronic converters the EM is capable of operating anywhere within the confines of the torque versus speed envelope shown in **Figure 3**. The shift of EM's operation from one quadrant to the other is generally very fast but it depends on the previous and new operating points. For example:

The driver wishes to overtake some vehicle and at that instant the EM is operating in motoring mode at 2500 rpm and producing a torque of 100Nm. After overtaking the driver slows to re-enter the traffic. When the driver slows, the EM has to decelerate and it acts as a generator and produces -100Nm of torque at a reduced speed, for example, of 15000 rpm. Initially the acceleration started the EM was operating in the field weakening region and during deceleration the EM has to operate in the constant torque region (**Figure 3**). Hence, the controller has to change its action from field weakening to constant torque regime and this process is slower than simply changing torque at constant speed. This changeover takes about 30ms to 100ms and is still much faster than the mechanical system.

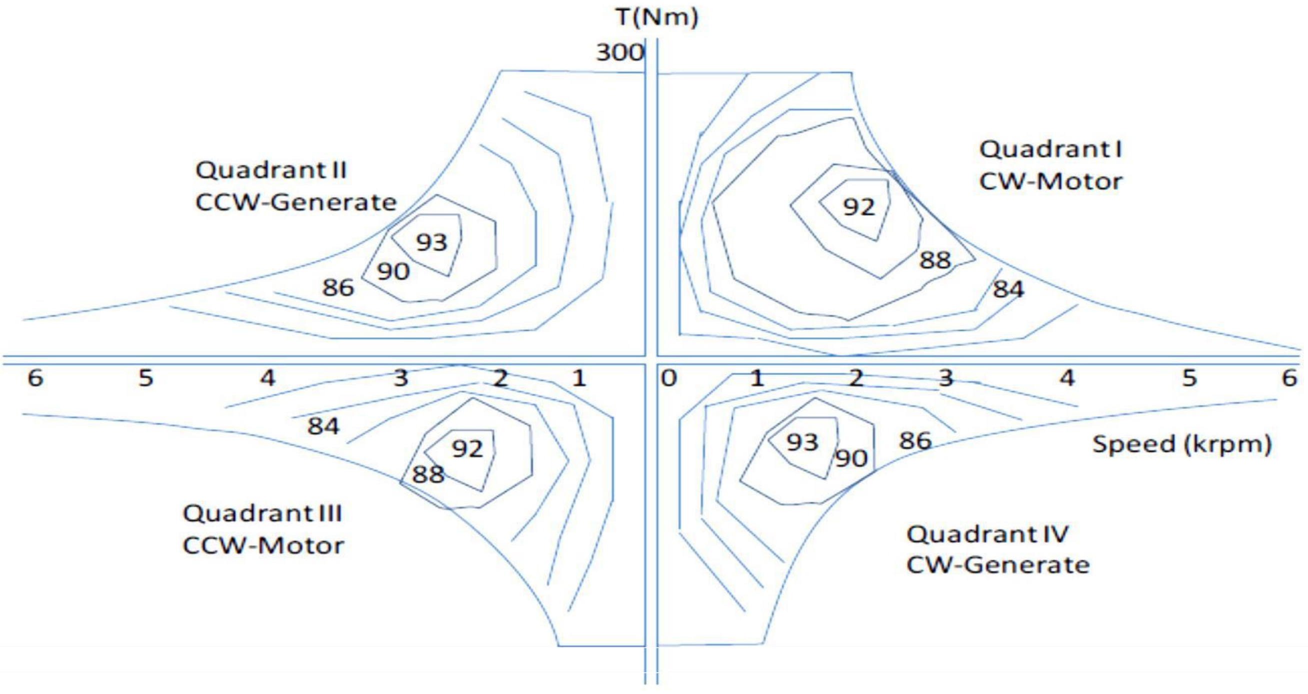


Figure 3: Torque versus speed curve of an EM for four quadrants [2]

EM Sizing

The EM is physically sized by its torque specification. Since, EM torque is determined by the amount of flux the iron can carry and the amount of current the conductors can carry, and can be expressed as

$$T = kABD^2L$$

where

k is proportionality constant

A is total ampere-turns per circumferential length [A/m] (1)

B is the Magnetic flux density [T]

D is the diameter of the rotor [m]

L is the length of the EM [m]

The two fundamental sizing constraints on the EM are:

i. Electric loading

ii. Magnetic loading

The electric loading is determined by the current carrying capacity of copper conductor and it is limited by its thermal dissipation. The bounds on the current density for copper is given by

$$J_{cu} = \begin{Bmatrix} 2\ \text{A/mm}^2 \text{ for continuous operation} \\ 6\ \text{A/mm}^2 \text{ for 3 minutes} \\ 20\ \text{A/mm}^2 \text{ for 30 seconds} \end{Bmatrix} \quad (2)$$

The magnetic loading, also defined by B, for EM is usually about 0.8Tesla. The EM sizing using **equation 1** gives the first approximation of the size of EM. Once the initial size of the EM is obtained, detailed analysis and modelling techniques such as Finite Element Methods can be used to obtain detailed design.

Selecting the energy storage technology

The choice of energy storage system technology is interleaved with vehicle tractive effort for the customer usage pattern anticipated. The following energy storage technologies are used in hybrid and electric vehicles.

1. Lead–acid technology

- Most cost effective secondary storage battery is the flooded lead–acid battery.
- Costs approximately \$0.50/Ah for a 6-cell module. (35 Rs /Ah)
- Maintenance free, valve regulated,
- The main disadvantage of lead–acid for hybrid vehicle traction application is its ***low cycle life*****.** Even deep discharge lead–acid batteries such as those used in battery-EV traction applications are not capable of much beyond 400 cycles (to 80% depth of discharge, DOD).

2. Nickel metal hydride

- NiMH have better energy and power density, and have an energy-lifetime that is nearly seven times longer than LAB.
- In today's market NiMH battery is the preferred high cycle life energy storage medium.
- One serious drawback is that the NiMH system does not respond well in cold temperatures.
- NiMH secondary battery systems are far superior to lead–acid in terms of efficiency and cycle life.
- Cost of approximately \$30/Ah in an 18 cell module. (Rs 2236.97/ Ah)
- In a mild hybrid vehicle application a NiMH battery system may be rated 26 Ah at 42V, whereas its alternative LAB would be rated 104 Ah at 42V.
- The difference is due to NiMH can deliver four times the energy of a LAB for the same Ah rating.

3. *Lithium ion and Lithium polymer*

- Plastic lithium ion technology has the potential to significantly impact vehicle integration issues currently impeding the application of hybrid power trains.
- The costs of lithium ion battery systems are today at least four times higher than SLI Lead acid batteries
- Lithium polymer is capable of high pulse power because the cell structure used is composed of a number of bicells in parallel instead of plates.
- According to the US Advanced Battery Consortium, lithium polymer technology is seen as the most promising long-term battery based on performance and life testing.
- But it has implementation issues related to its thin film construction and requires further progress in new electrode and electrolyte materials
- NiMH offers high power capability because it has good ionic conductivity in the potassium hydroxide electrolyte. Lithium ion, however, suffers from poor ionic transport unless very thin foil electrodes are used.
- Lithium ion does possess better energy density than NiMH.

4. *Fuel cell*

- Fuel cell applications have volumes in the 100s of units per year and consist of spacecraft powersupply as well as prototype applications to city busses.
- Costs are currently at or above $3000/kW, with most development funding provided by industrial developers. (Rs 2 Lakh)
- Fuel cell markets are now beginning to open up with applications as standby power generation units.
- Hydrogen is an energy carrier, and on a per mass basis, liquid hydrogen packs some three times the energy of gasoline. liquefaction of hydrogen may be impractical during the near term, so most manufacturers have resorted to gaseous storage in composite material canisters for mobile use.

A fuel cell, unlike a conventional battery is incapable of absorbing regeneration energy.

Near term durability, or operating life of the fuel cell stack, is consistent with automotive 10 year/150k miles.

If the vehicle is parked and the water freezes in the stack, then one or more of the fuel cells may crack, resulting in an open circuit and an inoperable stack.

5. *Ultra-capacitor*

- Ultra-capacitors will be competitive in hybrid propulsion systems when their cost drops below \$5/Wh.
- Cost is \$0.05/Wh a factor of 100 lower, but ultra-capacitors have many redeeming features.

A study was performed to determine the benefit of ultra-capacitor and battery parallel combinations, but using a switch interface to connect or disconnect either the ultra-capacitor or the battery from the 42V ISA component. The vehicle electrical loads remain connected to the 42V battery regardless of whether it is connected to the ISA or not.

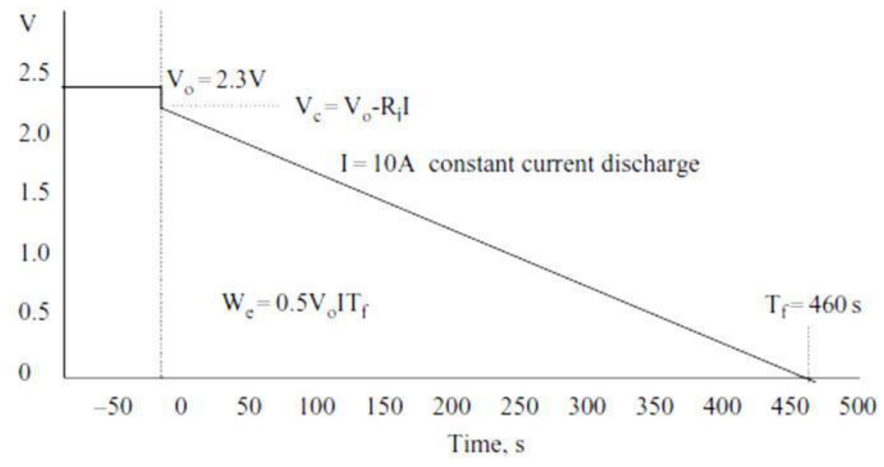


Figure 4.34 Ultra-capacitor constant current discharge testing

6. Flywheel

Comparison of battery types for vehicle propulsion

	Battery-EV					Hybrid vehicle					Temp.
	Energy	Power	Cycles	P/E	Energy-life	Energy	Power	Cycles	P/E	Energy-life	Range
Type	Wh/kg	W/kg	# @80% DOD	#	#Wh/kg	Wh/kg	W/kg	# @80% DOD	#	#Wh/kg	°C
VRLA	35	250	400	7	11 200	25	80	300	3.2	6000	−30, +70
NiMH	70	180	1200	2.6	67 200	40	1000	5500	25	176 000	0, +40
Lithium ion	90	220	600	2.4	43 200	65	1500	2500	23	130 000	0, +35
Li-Pol	140	300	800	2.1	89 600						0, +40

DEFINITION OF HYBRIDNESS

The definition of hybridness, H, is

$$H = \frac{\text{Sum of power of all traction motors}}{\text{Sum of traction motor+Engine power}} \tag{1}$$

Some hybrids have more than one motor/generator (M/G). Hybrids with motor-in-the-wheel and all-wheel-drive (AWD) have more than one motor. The definition uses the sum of all traction motors. The name, hybridization, is occasionally used for H.

As an example of hybridness consider a light delivery van with the propulsion:

Diesel engine: 110 kW at 3000 rpm

Electric motor: 23 kW; maximum torque 243 N-m at 500 rpm

$$H = \frac{23kW}{23+110kW} = 0.17 = 17\% \tag{2}$$