HYBRID ELECTRIC VEHICLES

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UNIT-I
INTRODUCTION OF HYBRID ELECTRIC VEHICLES

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- History Of Hybrid Electric Vehicles
- Social and Environmental Importance
- Impact Of modern Drive Trains on Energy Supplies
- Conventional Vehicles:
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HYBRID DEFINITION

- A hybrid vehicle combines any two power (energy) sources. Possible combinations include diesel/electric, gasoline/fly wheel, and fuel cell (FC)/battery.
- Typically, one energy source is storage, and the other is conversion of a fuel to energy.
- The combination of two power sources may support two separate propulsion systems. Thus to be a True hybrid, the vehicle must have at least two modes of propulsion.

Historical development (root) of Automobiles:

- In 1900, steam technology was advanced. The advantages of ***steam-powered cars*** included high performance in terms of power and speed. However, the disadvantages of steam-powered cars included poor fuel economy and the need to “fire up the boiler” before driving. Feed water was a necessary input for steam engine, therefore could not tolerate the loss of fresh water.
- *Gasoline cars* of 1900 were noisy, dirty, smelly, cantankerous, and unreliable. In comparison, electric cars were comfortable, quiet, clean, and fashionable.

INVENTION OF HYBRID VEHICLE :

- **1890 :**Jacob Lohner, a coach builder in Vienna, Austria, foresaw the need for an electric vehicle that would be less noisy than the new gas-powered cars. He commissioned a design for an electric vehicle from Austro-Hungarian engineer
- Ferdinand Porsche, who had recently graduated from the Vienna Technical College. Porsche's first version of the electric car used a pair of electric motors mounted in the front wheel hubs of a conventional car.

History of Hybrid Electric Vehicles

EARLY HYBRID VEHICLE :

- **1900:** Porsche showed his hybrid car at the Paris Exposition of 1900. A gasoline engine was used to power a generator which, in turn, drove a small series of motors.
- The electric engine was used to give the car a little bit of extra power. This method of ***series hybrid engine*** is still in use today, although obviously with further scope of performance improvement and greater fuel savings.

MODERN PERIOD OF HYBRID HISTORY :

- **1990s :** Automakers took a renewed interest in the hybrid, seeking a solution to dwindling energy supplies and environmental concerns and created modern history of hybrid car .
- **2000 :**Toyota Prius and Honda Insight became the first mass market hybrids to go on sale in the United States, with dozens of models following in the next decade.

Social and Environmental Importance

- As modern culture and technology continue to develop, the growing presence of global warming and irreversible climate change draws increasing amounts of concern from the world's population.
- It has only been recently, when modern society has actually taken notice of these changes and decided that something needs to change if the global warming process is to be stopped.
- Countries around the world are working to drastically reduce CO_2 emissions as well as other harmful environmental pollutants.

Social and Environmental Importance

Two environmental impact elements were accounted for in the:

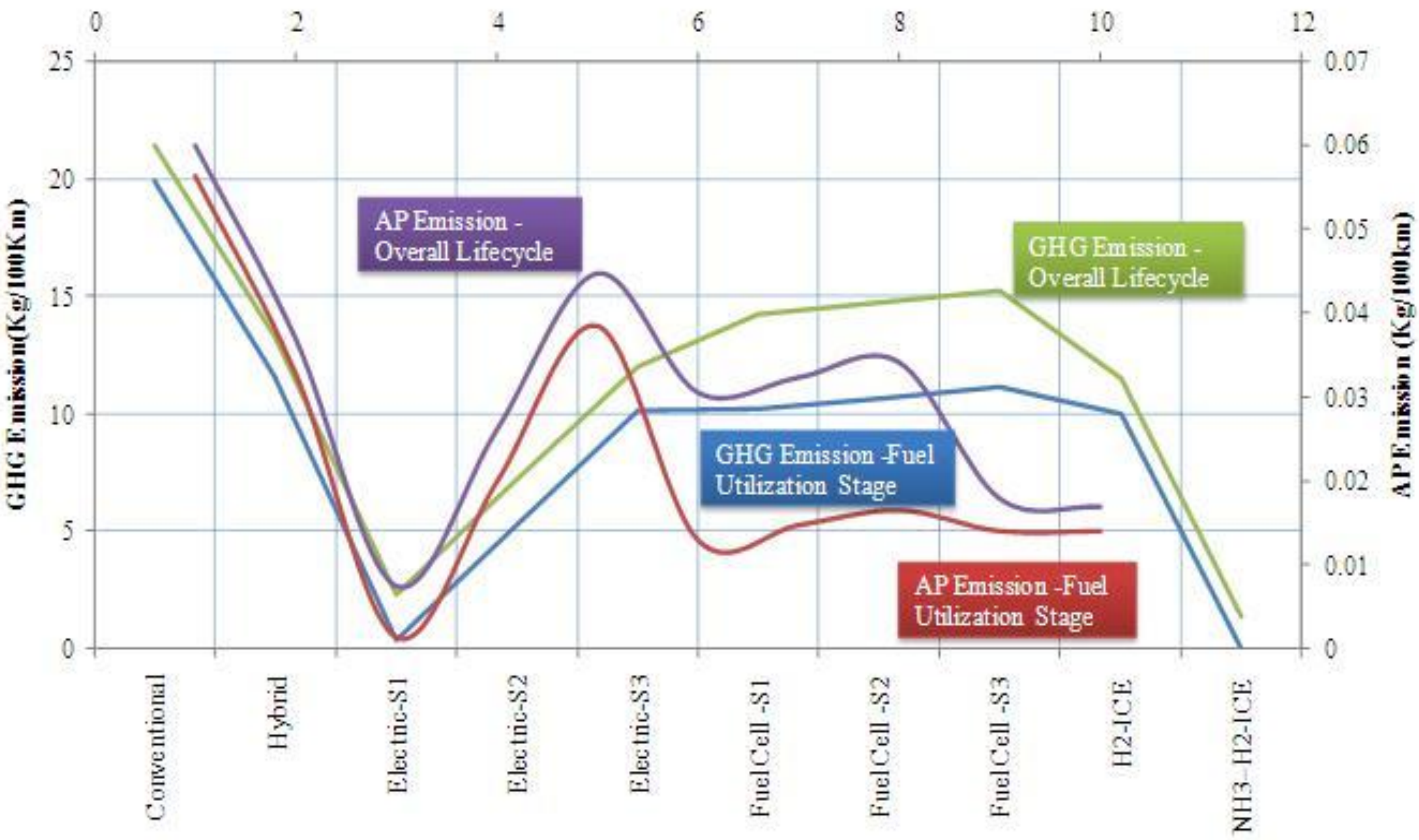
a. Air pollution (AP):

- At present, all vehicles rely on the combustion of hydrocarbon fuels to derive the energy necessary for their propulsion. Combustion is a reaction between the fuel and the air that releases heat and combustion products.
- The heat is converted to mechanical power by an engine and the combustion products are released into the atmosphere. A hydrocarbon is a chemical compound with molecules made up of carbon and hydrogen atoms.

B)GLOBAL WARMING:

- Global warming is a result of the "greenhouse effect" induced by the presence of carbon dioxide and other gases, such as methane, in the atmosphere.
- 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 and in many natural disasters that affect human populations.

Social and Environmental Importance



Impact Of Modern Drive-Trains on Energy supplies

In terms of overall energy efficiency, the conceptual advantages of a hybrid over a conventional vehicle are:

Regenerative braking:

- A hybrid can capture some of the energy normally lost as heat to the mechanical brakes by using its electric drive motor(s) in generator mode to break the vehicle

More efficient operation of the ICE, including reduction of idle:

- A hybrid can avoid some of the energy losses associated with engine operation at speed and load combinations where the engine is inefficient by using the energy storage device to either absorb part of the ICE's output or augment it or even substitute for it.

Smaller ICE:

- Since the storage device can take up a part of the load, the HEV's ICE can be down sized. The ICE may be sized for the continuous load and not for the very high short term acceleration load.
- This enables the ICE to operate at a higher fraction of its rated power, generally at higher fuel efficiency, during most of the driving.

There are counterbalancing factors reducing hybrids' energy advantage, including:

Potential for higher weight.

- Although the fuel-driven energy source on a hybrid generally will be of lower power and weight than the engine in a conventional vehicle of similar performance, total hybrid weight is likely to be higher than the conventional vehicle it replaces because of the added weight of the storage device, electric motor(s), and other components.

Electrical losses.

- Although individual electric drive train components tend to be quite efficient for one-way energy flows, in many hybrid configurations, electricity flows back and forth through components in a way that leads to cascading losses.

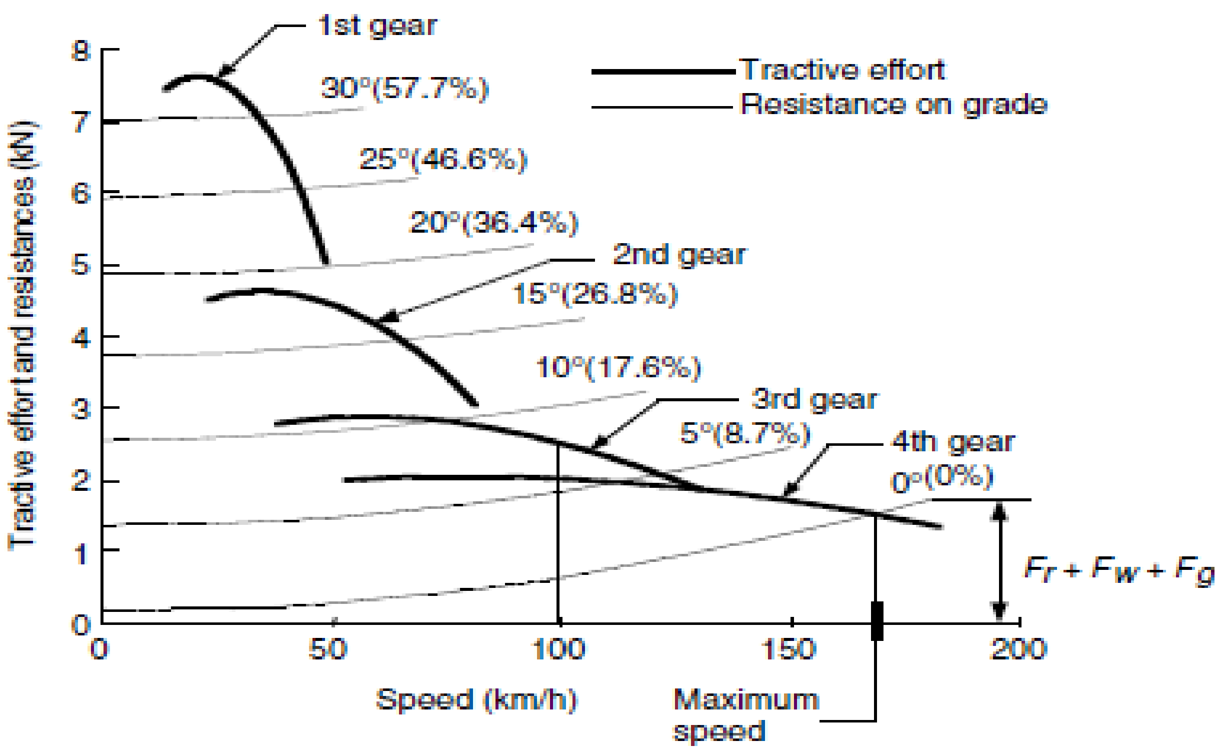
Conventional Vehicles

A conventional engine-driven vehicle uses its engine to translate fuel energy into shaft power, directing most of this power through the drive train to turn the wheels. Much of the heat generated by combustion cannot be used for work and is wasted, both because heat engines have theoretical efficiency limit. Moreover, it is impossible to reach the theoretical efficiency limit because:

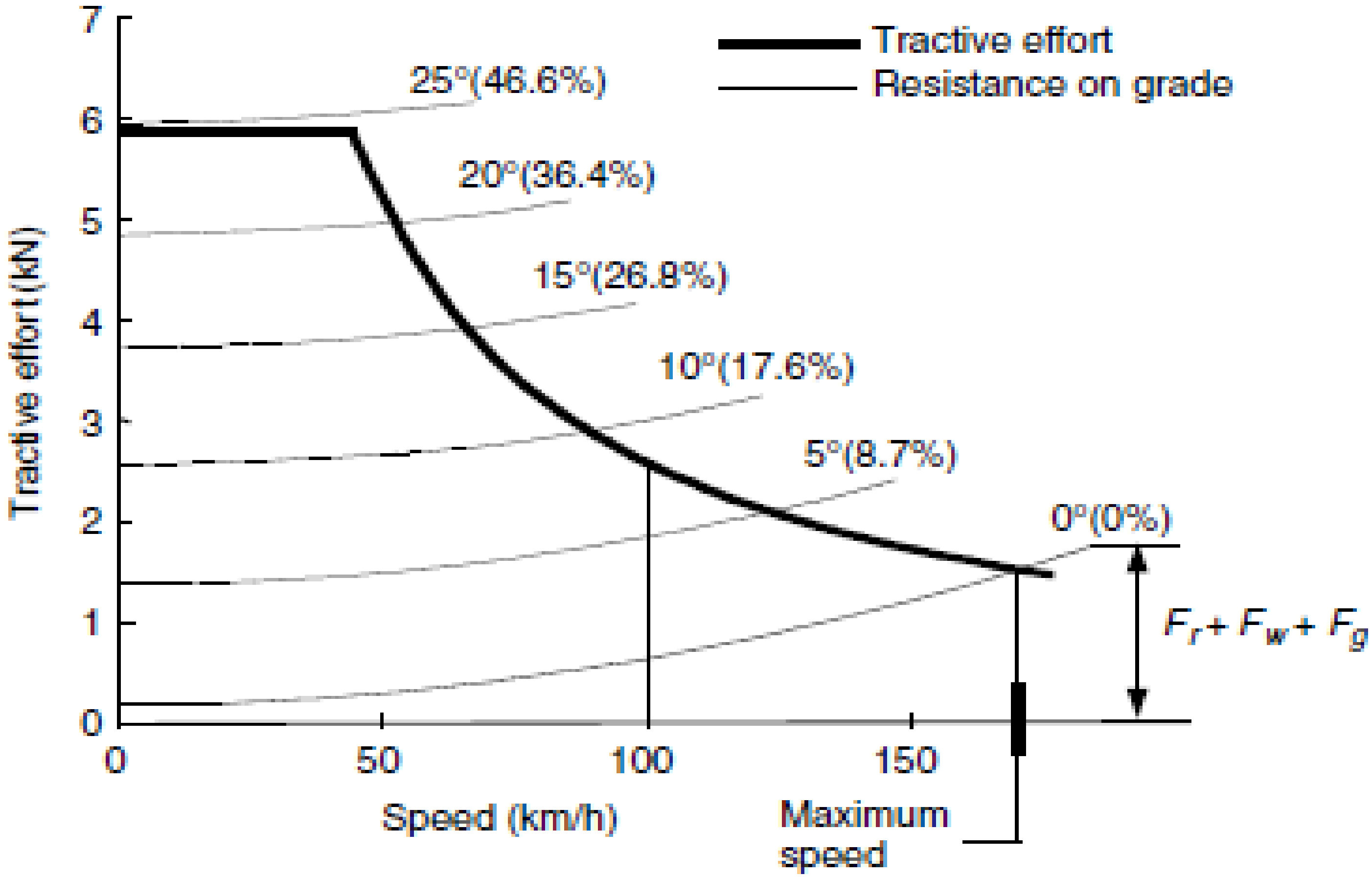
- Some heat is lost through cylinder walls before it can do work
- Some fuel is burned at less than the highest possible pressure
- Fuel is also burned while the engine is experiencing negative load (during braking) or when the vehicle is coasting or at a stop, with the engine idling.

BASIC VEHICLE PERFORMANCE

- The performance of a vehicle is usually described by its maximum cruising speed, gradeability, and acceleration.
- **Tractive effort of a gasoline engine-powered vehicle with multispeed transmission and itsresistance:**

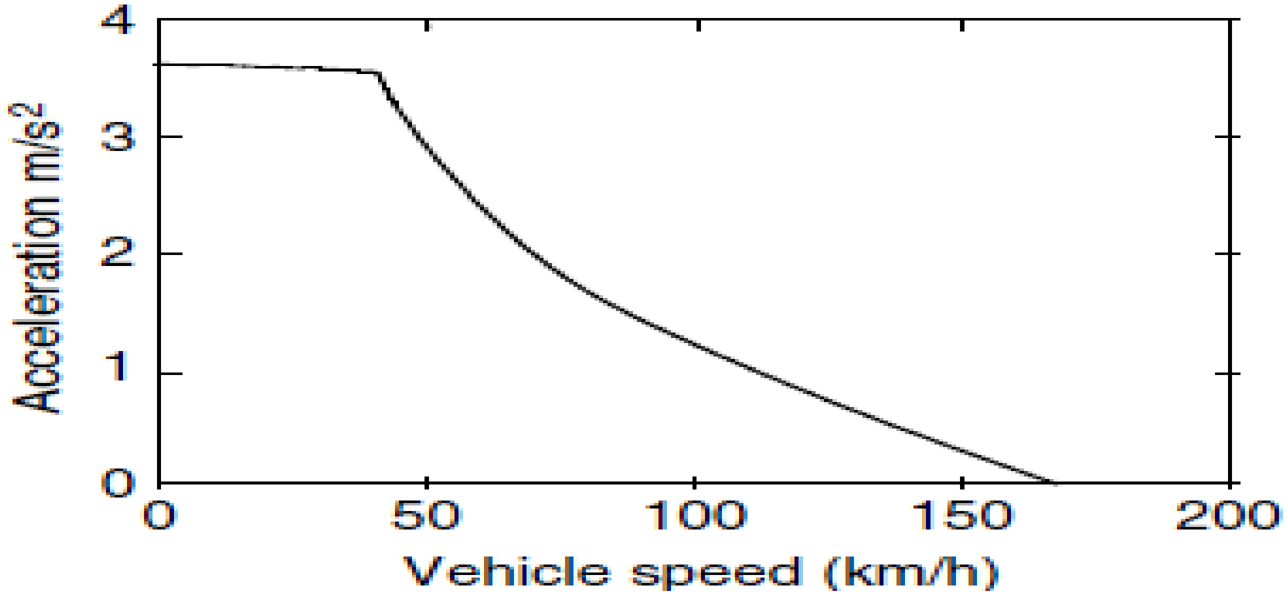


Tractive effort of an electric motor-powered vehicle with single-speed transmission and its resistance:



Acceleration Performance:

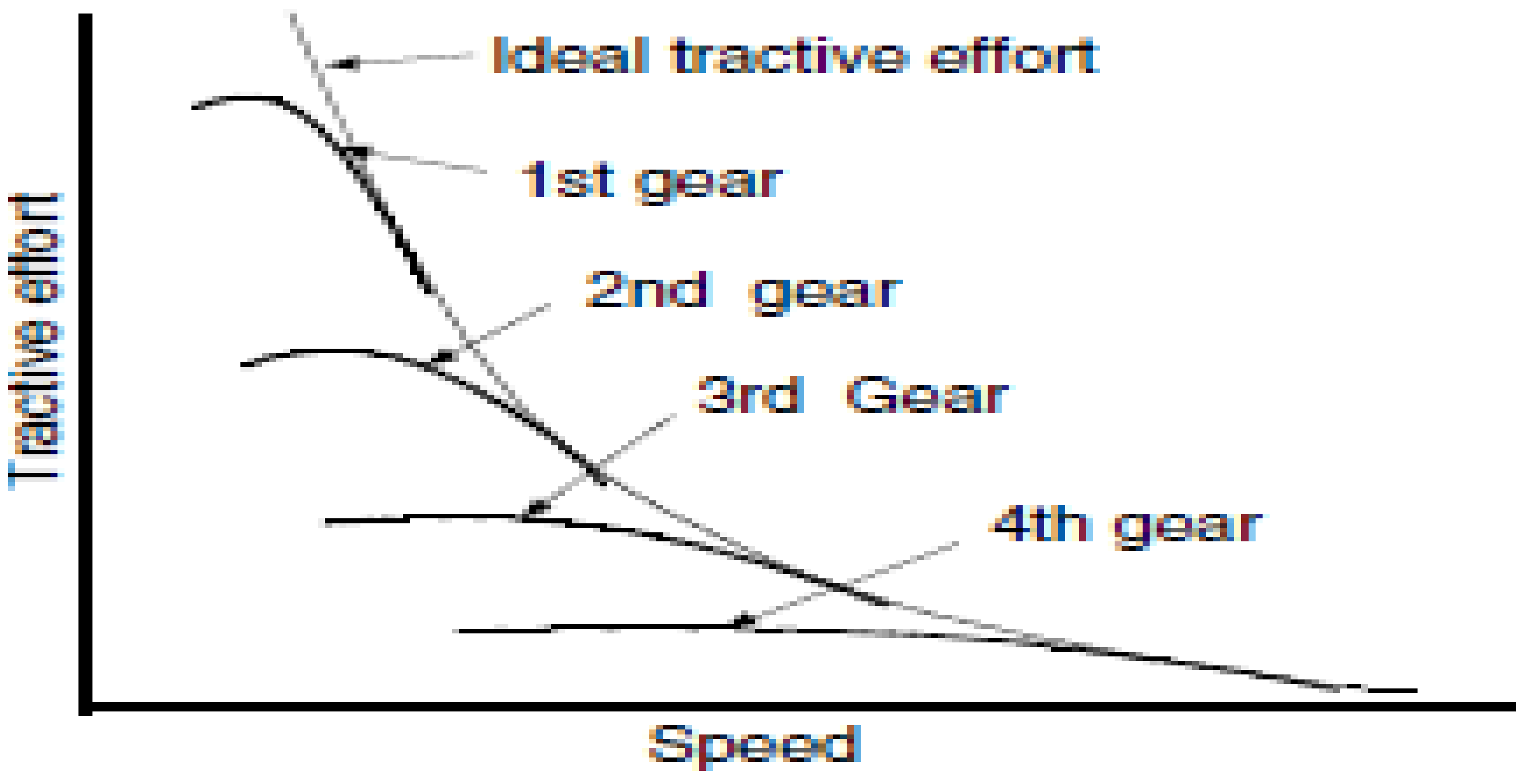
- Acceleration of an electric machine-powered vehicle with single-gear transmission



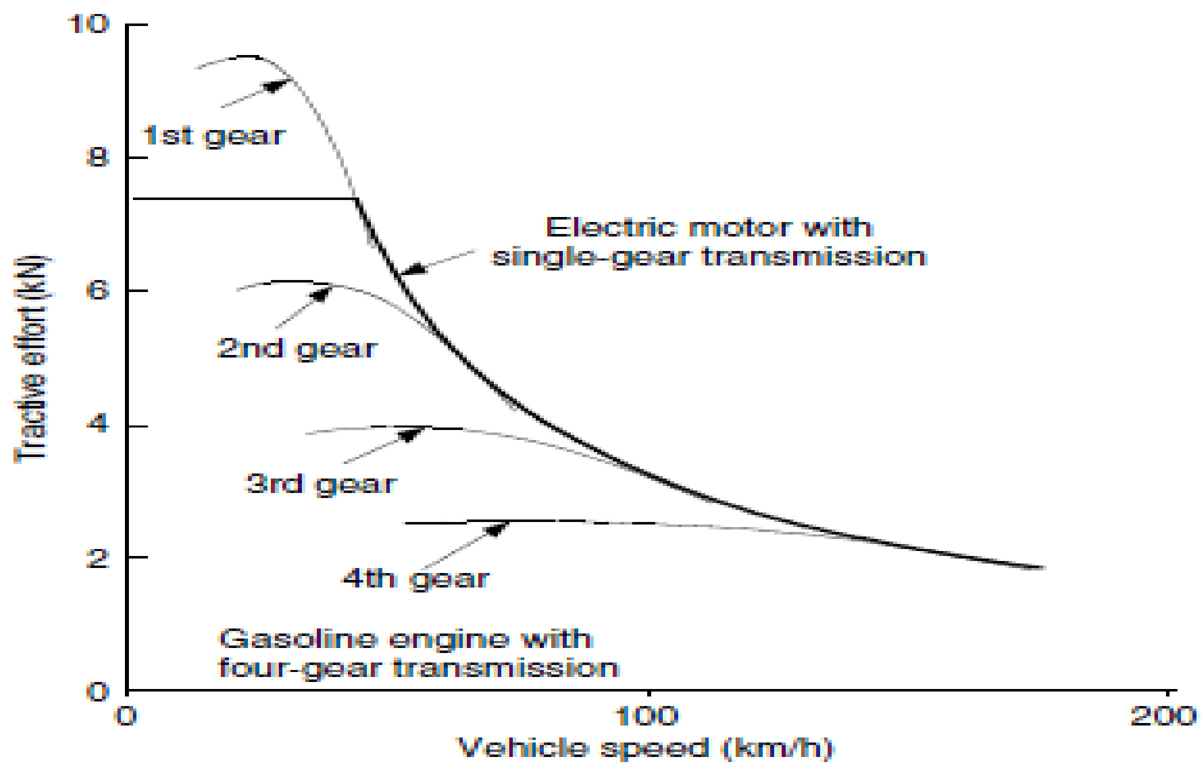
TRANSMISSION CHARACTERISTICS

- The transmission requirements of a vehicle depend on the characteristics of the power plant and the performance requirements of the vehicle.
- As mentioned previously, a well-controlled electric machine such as the power plant of an electric vehicle will not need a multi gear transmission.
- However, an internal combustion engine must have a multi gear or continuously varying transmission to multiply its torque at low speed.
- The term transmission here includes all those systems employed for transmitting engine power to the drive wheels.

Tractive effort characteristics of a gasoline Engine powered vehicle



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



TRANSMISSION CHARACTERISTICS

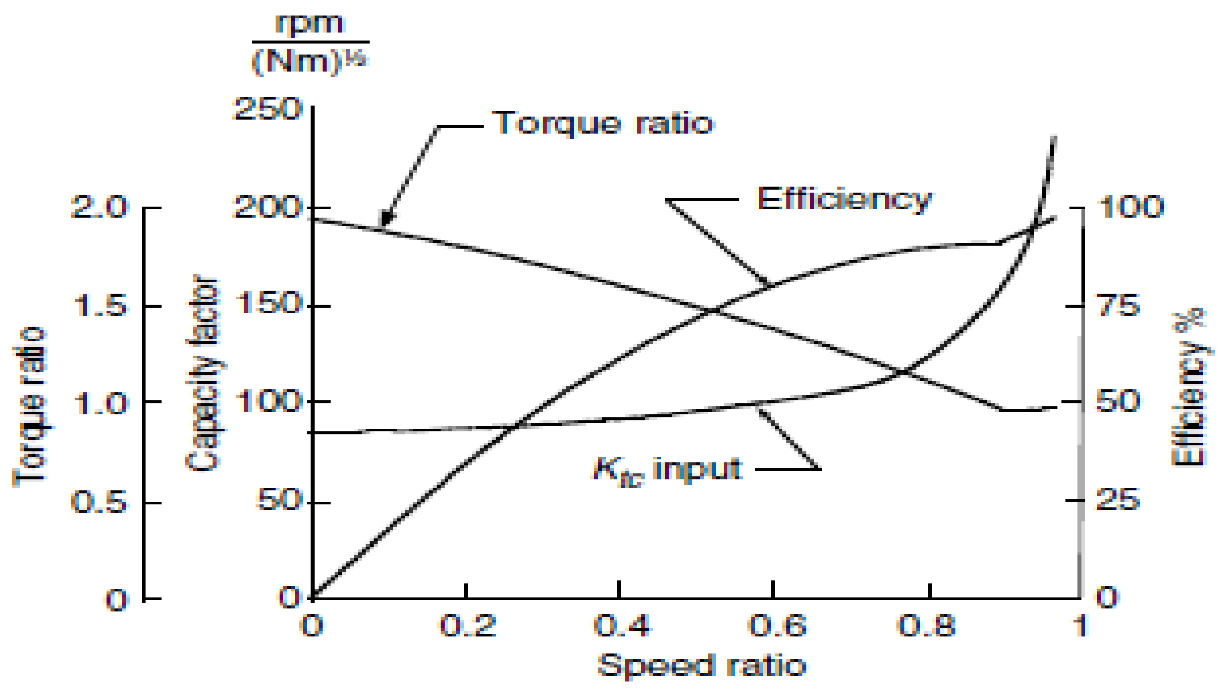
Hydrodynamic Transmission:

- Hydrodynamic transmissions use fluid to transmit power in the form of torque and speed and are widely used in passenger cars.
- They consist of a torque converter and an automatic gearbox. The torque converter consists of at least three rotary elements known as the impeller (pump), the turbine, and the reactor.
- The impeller is connected to the engine shaft and the turbine is connected to the output shaft of the converter, which in turn is coupled to the input shaft of the multispeed gearbox.

TRANSMISSION CHARACTERISTICS

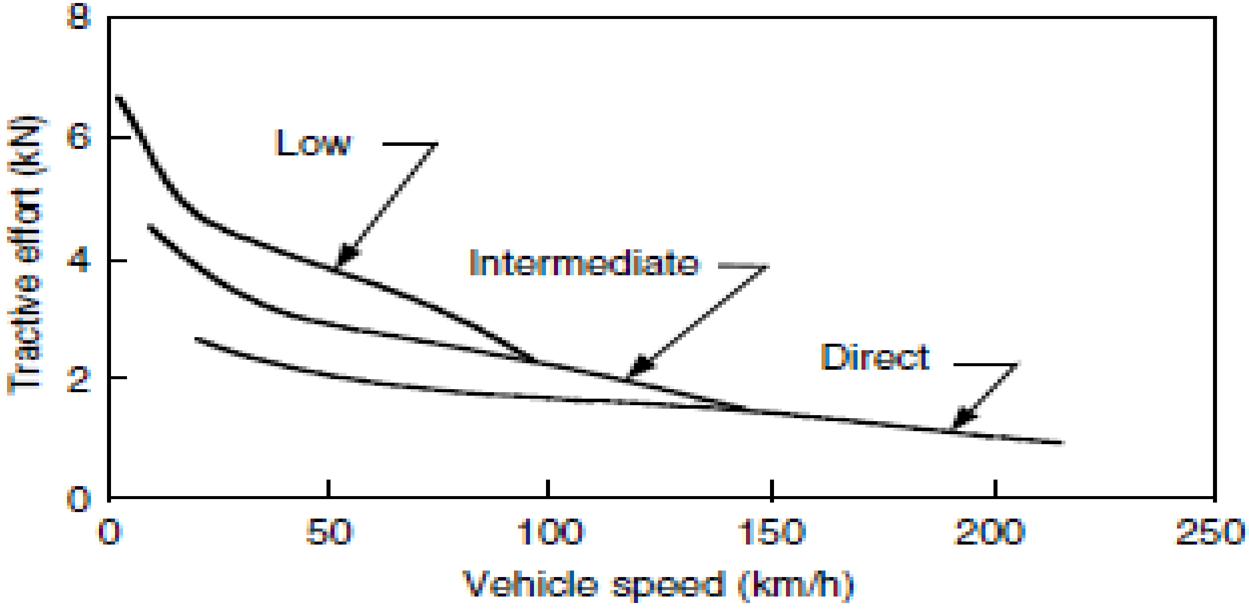
- **Hydrodynamic Transmission:**

Performance characteristics of a torque converter:



Hydrodynamic Transmission

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



UNIT-II
HYBRID ELECTRIC DRIVE TRAINS

INTODUCTION OF HYBRID DRIVE TRAIN

The term hybrid vehicle refers to a vehicle with at least two sources of power. Hybrid-electric vehicle indicates that one source of power is provided by an electric motor. there are many types of HEVs, such as:

- the gasoline ICE and battery
- diesel ICE and battery
- battery and FC
- battery and capacitor
- battery and flywheel
- Battery and battery hybrids.

Series Hybrid System*:*

In case of series hybrid system (**Figure 4a**) the mechanical output is first converted into electricity using a generator. Conceptually, it is an ICE assisted Electric Vehicle (EV). The advantages of series hybrid drivetrains are

- mechanical decoupling between the ICE and driven wheels allows the IC engine operating at its very narrow optimal region as shown in **Figure5**.
- nearly ideal torque-speed characteristics of electric motor make multi-gear transmission unnecessary.
- However, a series hybrid drivetrain has the following disadvantages:
- 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.

- **Series Hybrid System*:***

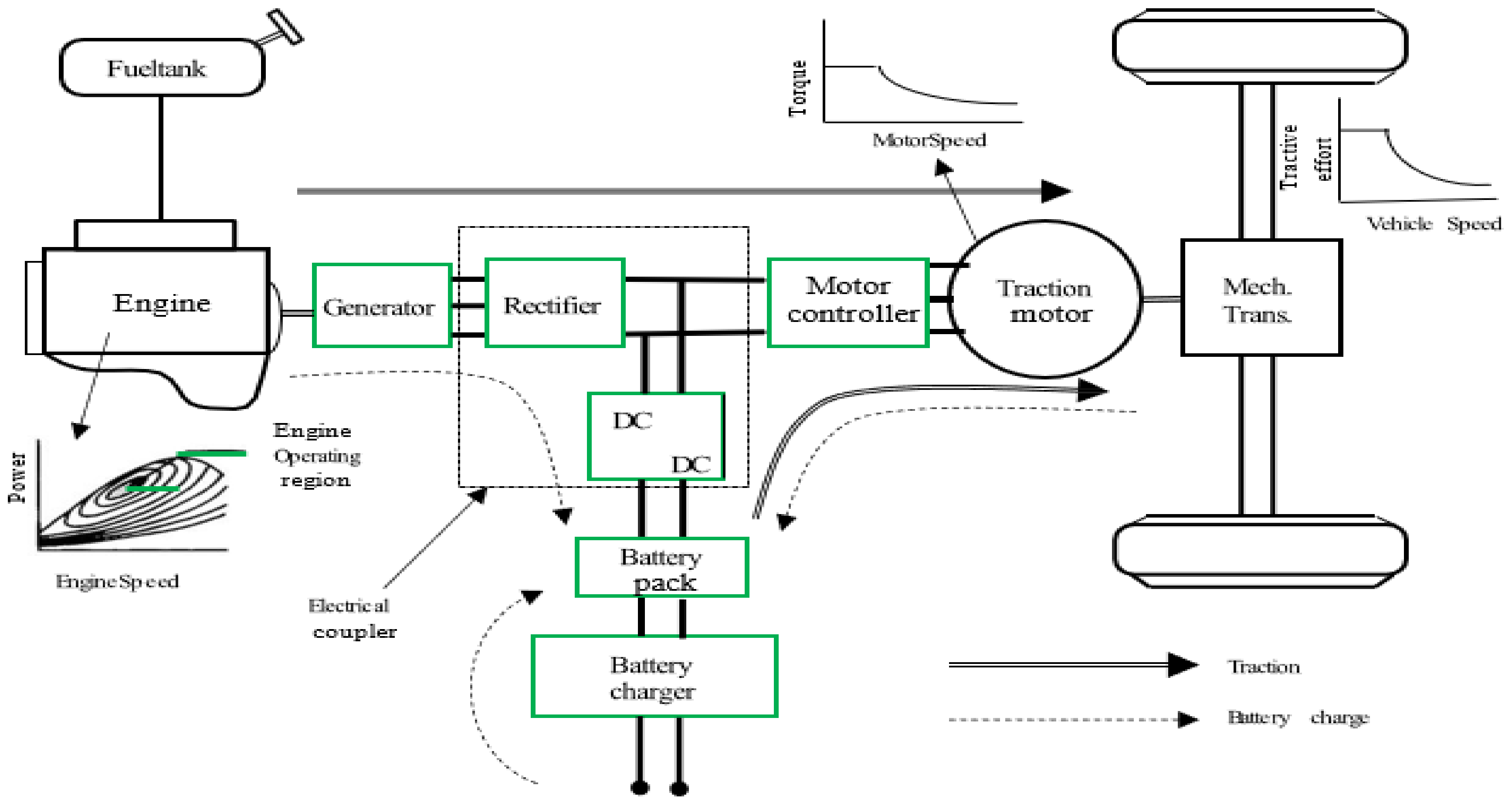


Figure 5: Detailed Configuration of Series Hybrid Vehicle [1]

PARALLEL HYBRID SYSTEM:

The parallel HEV allows both ICE and electric motor (EM) to deliver power to drive the wheels. Since both the ICE and EM are coupled to the drive shaft of the wheels via two clutches, the propulsion power may be supplied by ICE alone, by EM only or by both ICE and EM. The advantages of the parallel hybrid drivetrain are:

- both engine and electric motor directly supply torques to the driven wheels and no energy form conversion occurs, hence energy loss is less
- compactness due to no need of the generator and smaller traction motor. The drawbacks of parallel hybrid drivetrains are:
- mechanical coupling between the engines and the driven wheels, thus the engine operating points cannot be fixed in a narrow speed region.
- The mechanical configuration and the control strategy are complex compared to series hybrid drive train.
- Due to its compact characteristics, small vehicles use parallel configuration. Most passenger cars employ this configuration.

INTODUCTION OF HYBRID DRIVE TRAIN

Series-Parallel System:

In the series-parallel hybrid , the configuration incorporates the features of both the series and parallel HEVs. However, this configuration needs an additional electric machine and a planetary gear unit making the control complex.

Complex Hybrid System:

- The complex hybrid system involves a complex configuration which cannot be classified into the above three kinds.
- The complex hybrid is similar to the series-parallel hybrid since the generator and electric motor is both electric machines.
- However, 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. The major disadvantage of complex hybrid is higher complexity.

INTODUCTION OF HYBRID DRIVE TRAIN

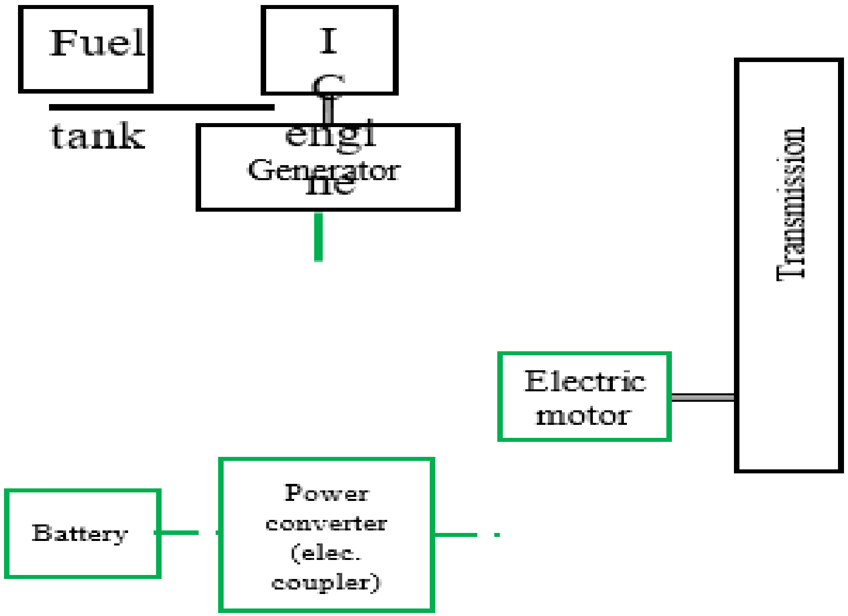


Figure 4a: Series hybrid [1]

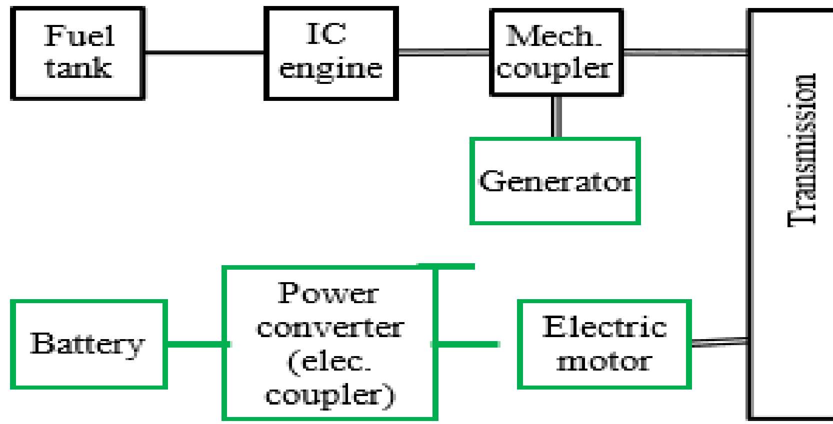
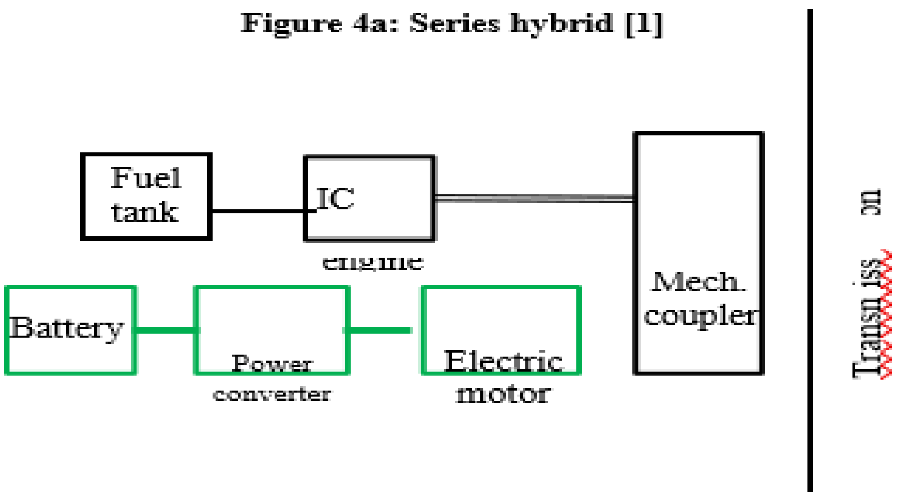
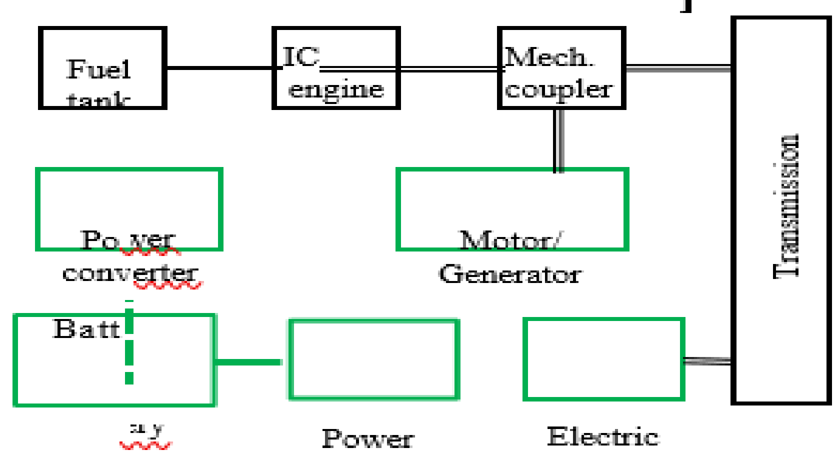


Figure 4b: Series-Parallel hybrid[1]





power flow control in hybrid drive train topologies

- Due to the variations in HEV configurations, different power control strategies are necessary to regulate the power flow to or from different components. All the control strategies aim satisfy the following goals:
  - maximum fuel efficiency
  - minimum emissions
  - minimum system costs
  - good driving performance
- The design of power control strategies for HEVs involves different considerations such as:
  - ***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.

POWER FLOW CONTROL IN SERIES HYBRID:

- In the series hybrid system there are four operating modes based on the power flow:
  - **Mode 1:** During startup (**Figure 1a**), normal driving or acceleration of the series HEV, both the ICE and battery deliver electric energy to the power converter which then drives the electric motor and hence the wheels via transmission.
  - **Mode 2:** At light load (**Figure 1b**), the ICE output is greater than that required to drive the wheels. Hence, a fraction of the generated electrical energy is used to charge the battery. The charging of the batter takes place till the battery capacity reaches a properlevel.
  - **Mode 3:** During braking or deceleration (**Figure 1c**), the electric motor acts as a generator, which converts the kinetic energy of the wheels into electricity and this, is used to charge thebattery.

power flow control in hybrid drive train topologies

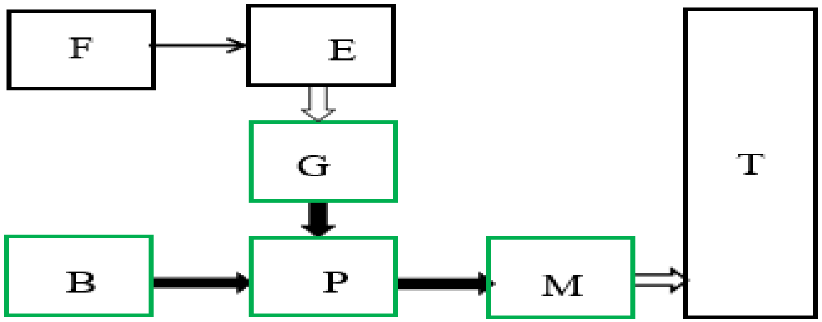


Figure 1a: Mode 1, normal driving or acceleration

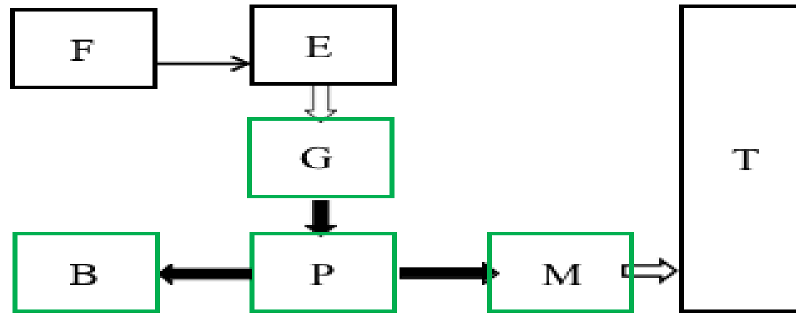


Figure 1b: Mode 2, light load

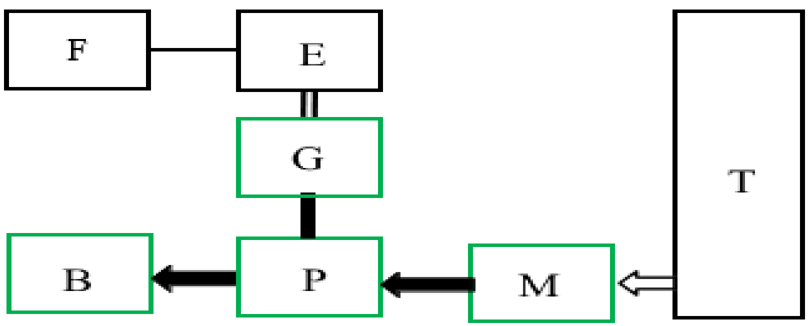


Figure 1c: Mode 3, braking or deceleration [1]

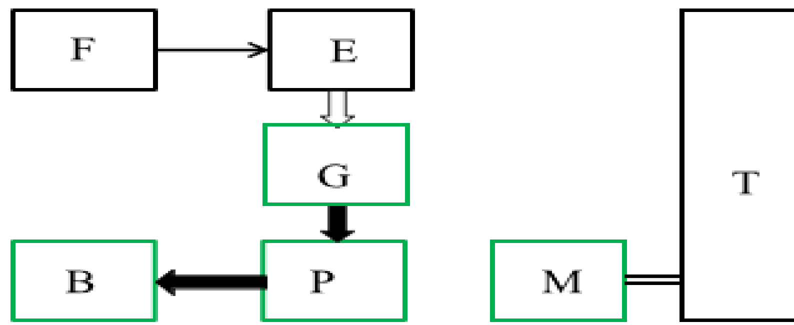


Figure 1d: Mode 4, vehicle at stop

B-Battery
E: ICE
F: Fueltank

G: Generator
M: Motor
P: PowerConverter

Electrical link
Hydraulic link
Mechanical link

T: Transmission (including brakes, clutches and gears)

Power Flow Control in Parallel Hybrid

- The parallel hybrid system has four modes of operation. These four modes of operation are
  - **Mode 1:** During start up or full throttle acceleration (**Figure 2a)**; both the ICE and the EM share the required power to propel the vehicle. Typically, the relative distribution between the ICE and electric motor is80-20%.
  - **Mode 2:** During normal driving (**Figure 2b**), the required traction power is supplied by the ICE only and the EM remains in off mode.
  - **Mode 3:** During braking or deceleration (**Figure 2c**), the EM acts as a generator to charge the battery via the power converter.

power flow control in hybrid drive train topologies

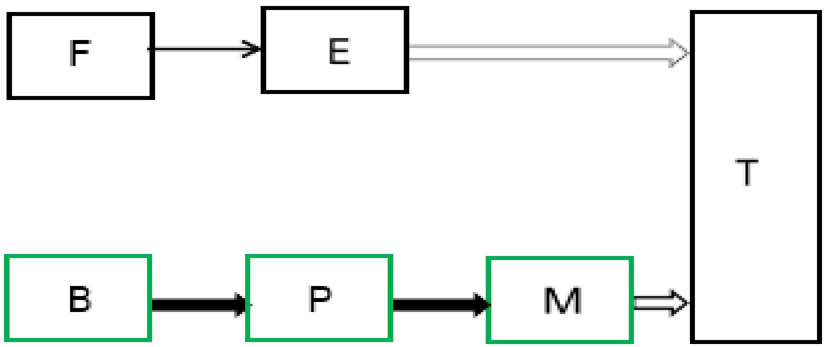


Figure 2a: Mode 1, start up

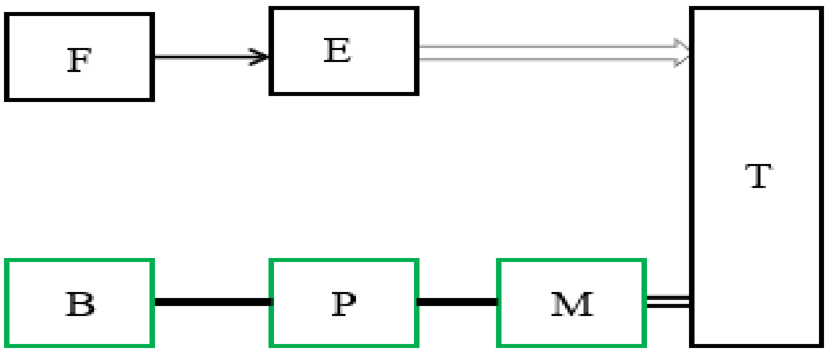


Figure 2b: Mode 2, normal driving

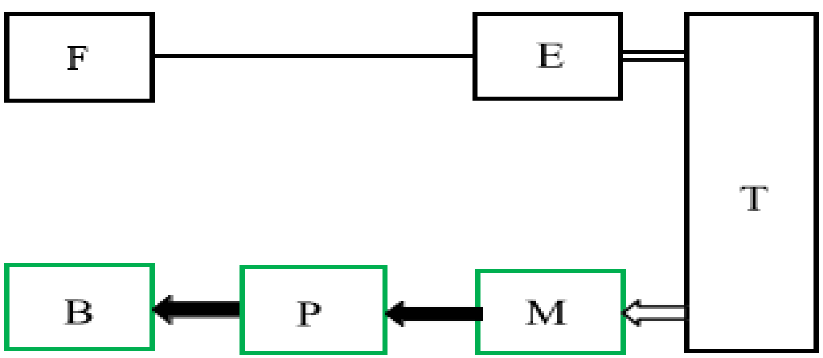


Figure 2c: Mode 3, braking or deceleration [1]

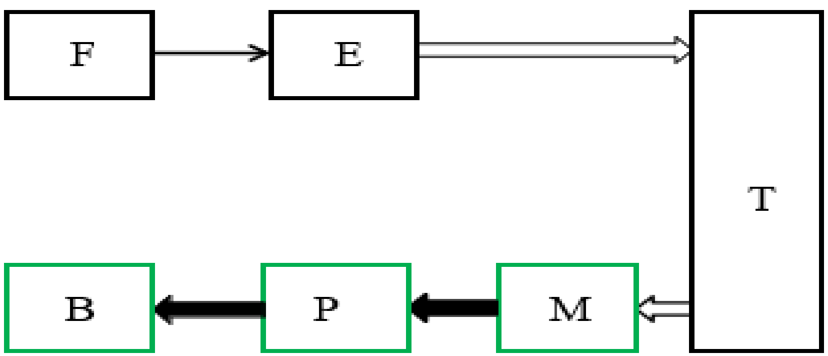


Figure 2d: Mode 4, light load

B:Battery
E: ICE
F: Fuel tank

G: Generator
M: Motor
P: Power Converter

Electrical link
Hydraulic link
Mechanicallink

Power Flow Control Series-Parallel Hybrid

- The series-parallel hybrid system involves the features of series and parallel hybrid systems. Hence, a number of operation modes are feasible. Therefore, these hybrid systems are classified into two categories: **the ICE dominated** and the **EM dominated**.
- The various operating modes of **ICE dominated** system are:
  - **Mode 1:** At startup (**Figure 3a)**, the battery solely provides the necessary power to propel the vehicle and the ICE remains in off mode.
  - **Mode 2:** During full throttle acceleration (**Figure 3b**), both the ICE and the EM share the required traction power.
  - **Mode 3:** During normal driving (**Figure 3c**), the required traction power is provided by the ICE only and the EM remains in the off state.

power flow control in hybrid drive train topologies

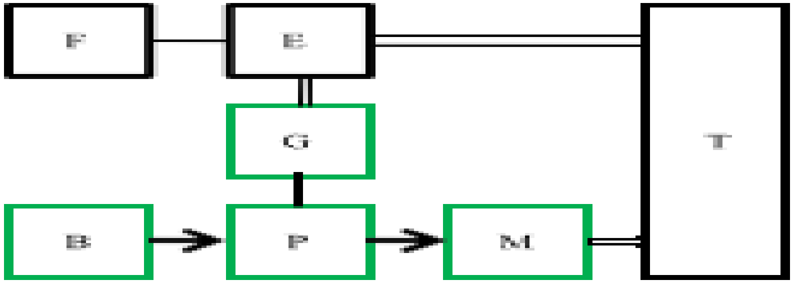


Figure 3a: Mode 1, startup [1]

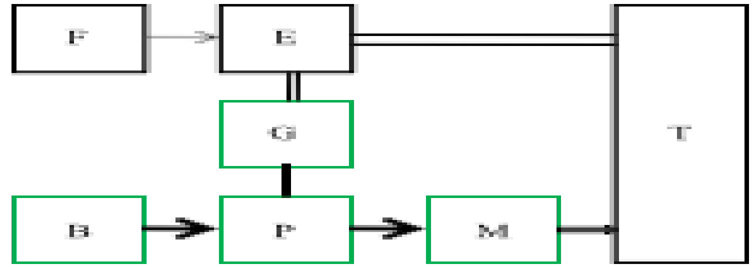


Figure 3b: Mode 2, acceleration[1]

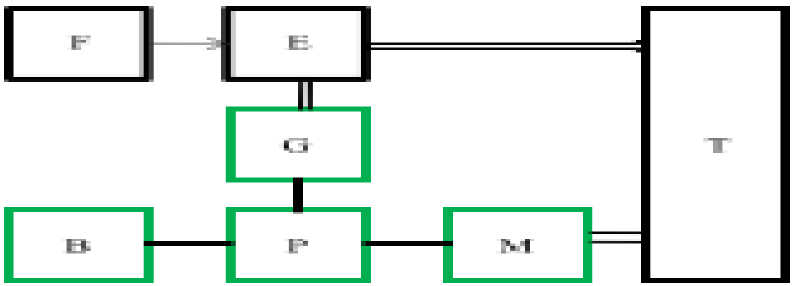


Figure 3c: Mode 3, normal drive[1]

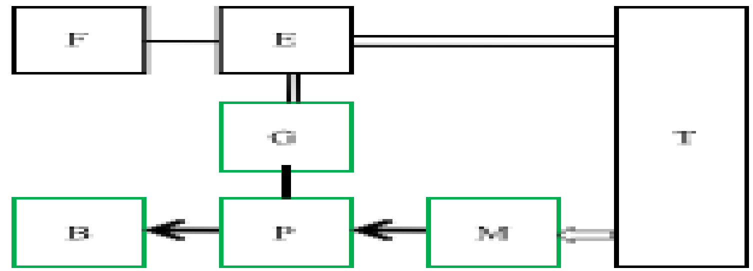


Figure 3d: Mode 4, braking or deceleration[1]

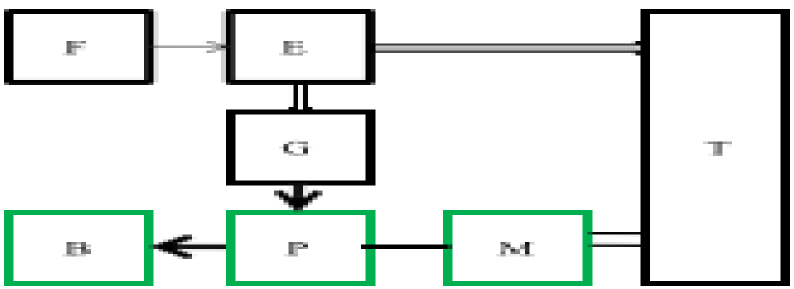


Figure 3e: Mode 5, battery charging during driving[1]

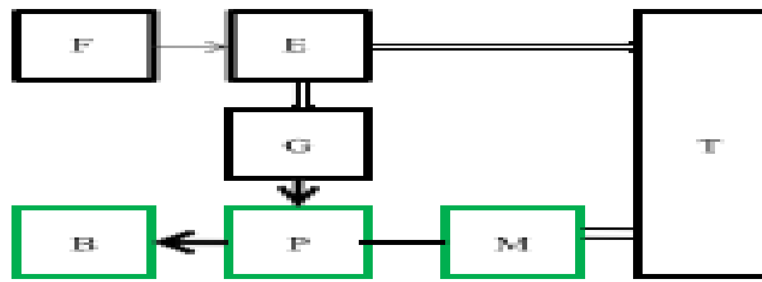


Figure 3f: Mode 6, battery charging during standstill [1]

B : Battery
E : ICE
F : Fuel Tank
G : Generator
M : Motor
P : Power Converter
T : Transmission(including brakes, clutches and gears)

Electrical link
Hydraulic link
Mechanical link

power flow control in hybrid drive train topologies

- The complex hybrid vehicle configurations are of two types:
  - Front hybrid rear electric
  - Front electric and rear hybrid

Both the configurations have six modes of operation:

- **Mode 1:** During startup (**Figure 5a**), the required traction power is delivered by the EMs and the engine is in off mode.
- **Mode 2:** During full throttle acceleration (**Figure 5b**), both the 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:** During normal driving (**Figure 5c**), the ICE delivers power to propel the front wheel and to drive the first EM as a generator to charge the battery.

power flow control in hybrid drive train topologies

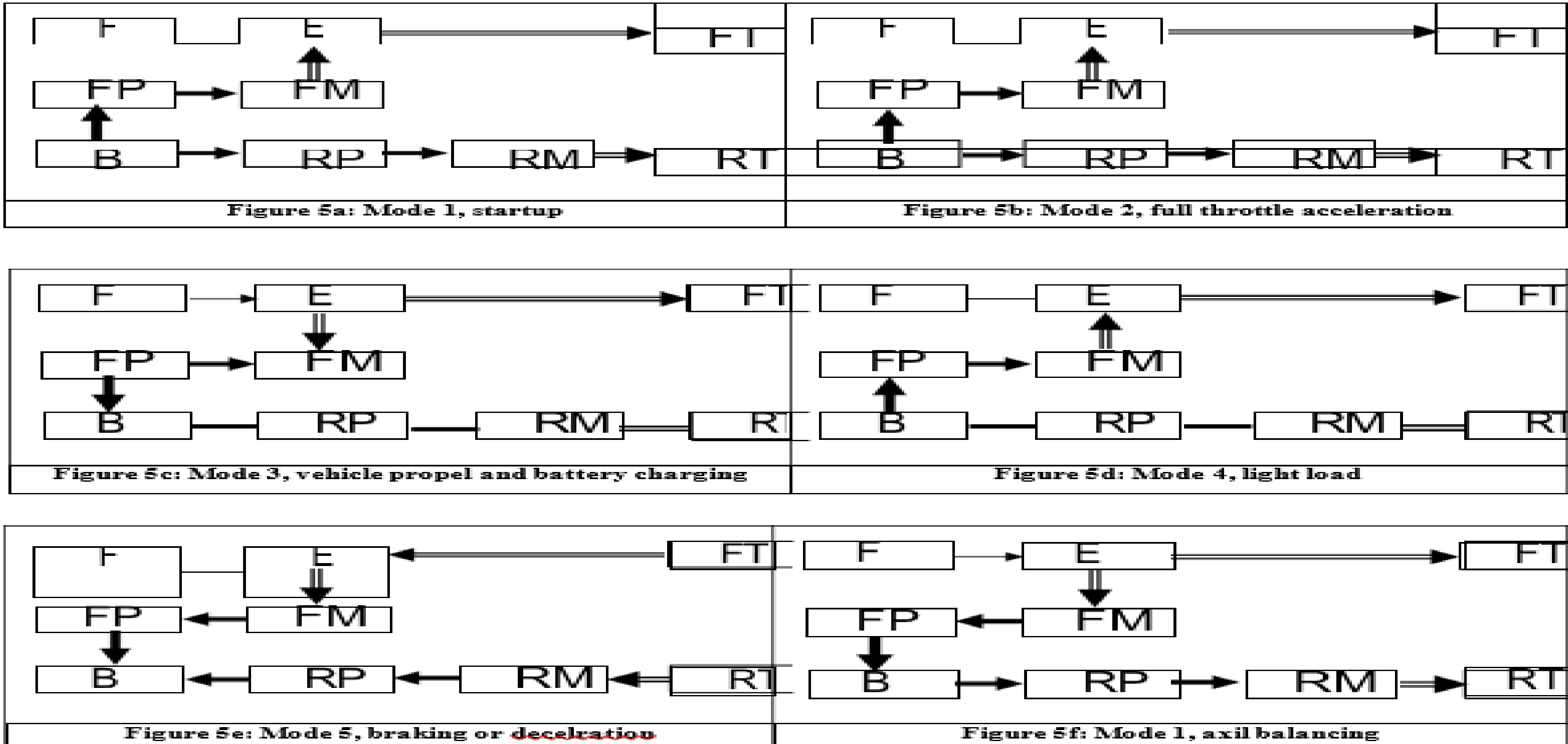


Figure 5a: Mode 1, startup

Figure 5b: Mode 2, full throttle acceleration

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

Figure 5d: Mode 4, light load

Figure 5e: Mode 5, braking or decelration

Figure 5f: Mode 1, axil balancing

B: Battery FM: Frontmotor FP: Front power converter FT: Frontaxel transmission E: ICE F: Fuel tank

RM: Rear motor RP: Rear power converter RT: Rear axle transmission[1]

Electricallink

Hydraulic link

Mechanicallink

- **Power Flow Control Complex Hybrid Control**

The complex hybrid vehicle configurations are of two types:

- Front hybrid rear electric
- Front electric and rear hybrid

Both the configurations have six modes of operation:

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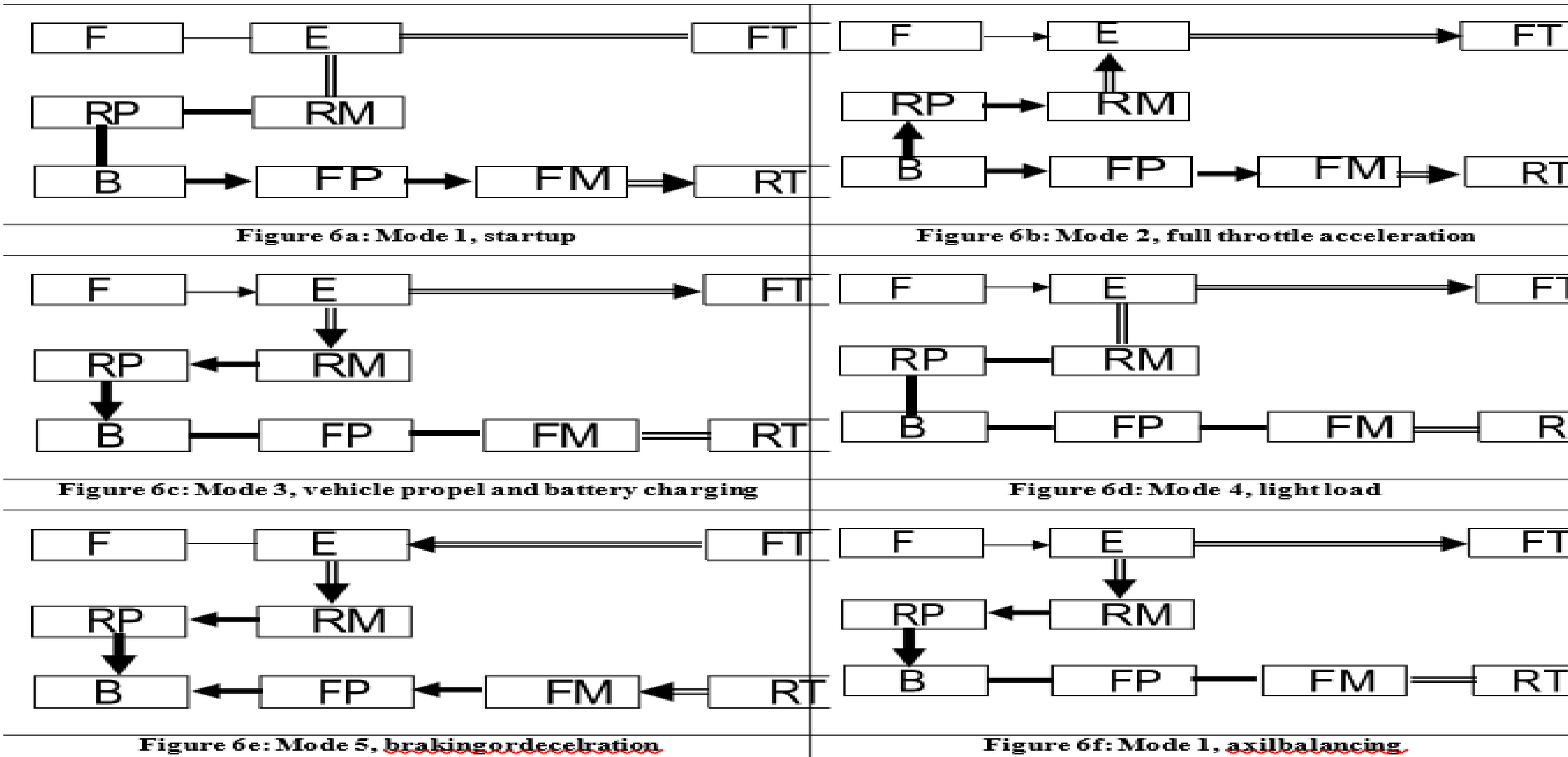
- **Mode 3:** During normal driving (**Figure 5c**), the ICE delivers power to propel the front wheel and to drive the first EM as a generator to charge the battery.

power flow control in hybrid drive train topologies



B:Battery RM:Rearmotor FP: Front power converter FT: Front axle transmission E: ICE F: Fueltank
RM:Rear motor RP: Rear power converter RT: Rear axle transmission[1]

Electricallink
Hydrauliclink
Mechanicallink

Electric Vehicle (EV) Configurations

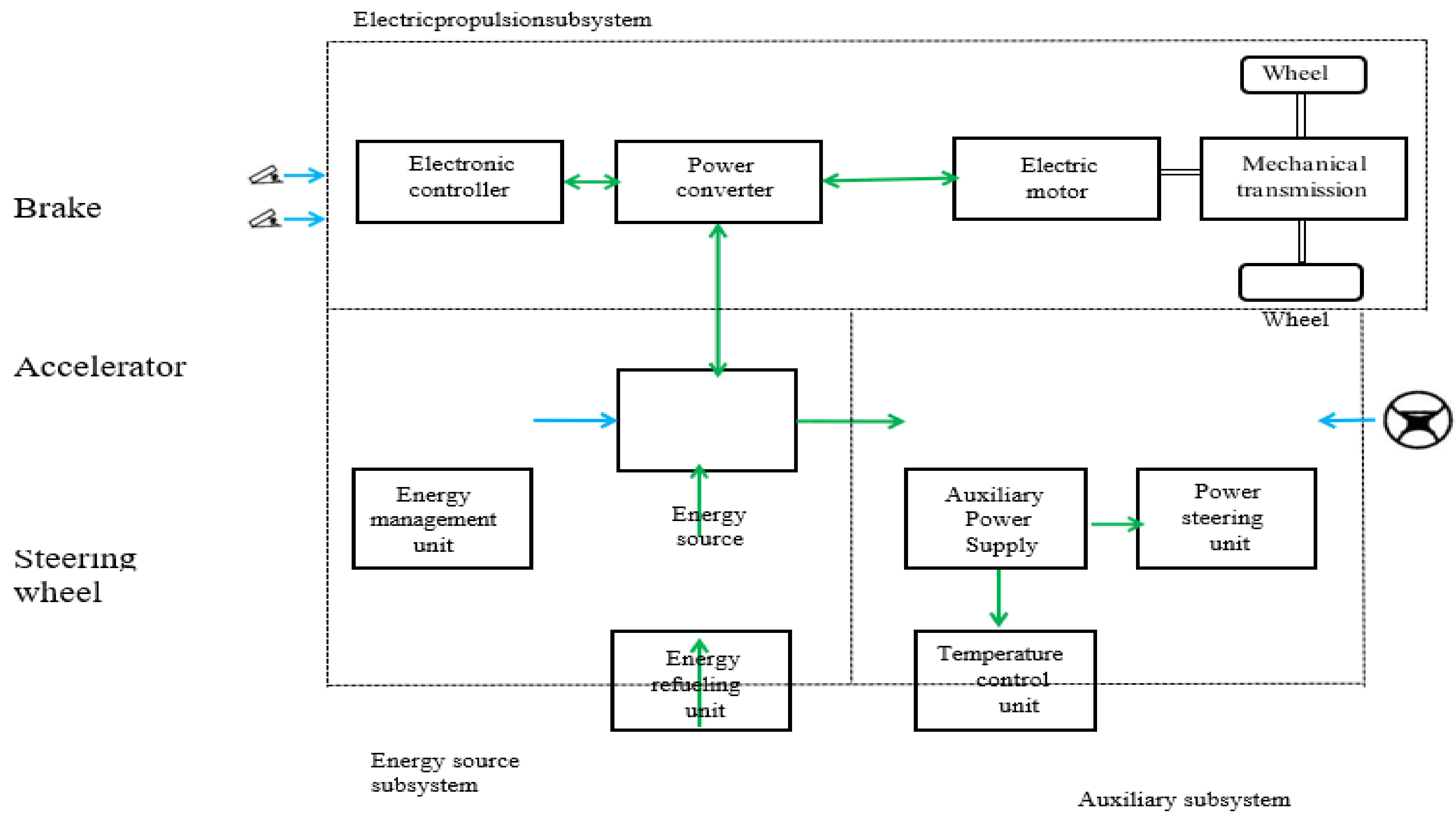
Compared to HEV, the configuration of EV is flexible. The reasons for this flexibility are:

- The energy flow in EV is mainly via flexible electrical wires rather than bolted flanges or rigid shafts. Hence, the general configuration of the EV is shown. The EV has three major subsystems:
- Electric propulsion
- Energy source
- Auxiliary system

The electric propulsion subsystem comprises of:

- The electronic controller
- Power converter
- Electric Motor (EM)
- Mechanical transmission
- Driving wheels

General Configuration of a Electric Vehicle :



Electric Vehicle (EV) Drivetrain Alternatives Based on Drivetrain Configuration :

There are many possible EV configurations due the variations in electric propulsion and energy sources. Based on these variations, six alternatives are possible as shown in **Figure 3**. These six alternativesare

- In **Figure 3a** a single EM configuration with gearbox (GB) and a clutch is shown. It consists of an EM, a clutch (C), a gearbox, and a differential (D). The clutch enables the connection or disconnection of power flow from EM to the wheels. The gear consists of a set of gears with different gear ratios. In Figure 3b a single EM configuration without the gear
- box and the clutch is shown. The advantage of this configuration is that the weight of the transmission is reduced

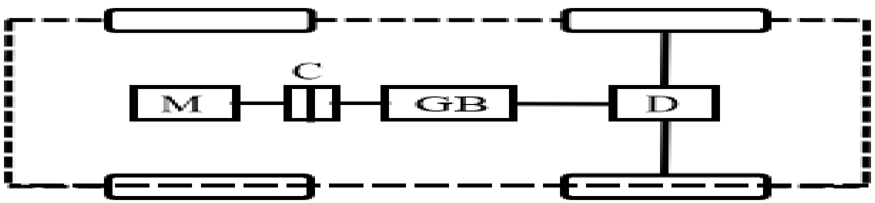


Figure 3a: EV configuration with clutch, gearbox and differential [1]

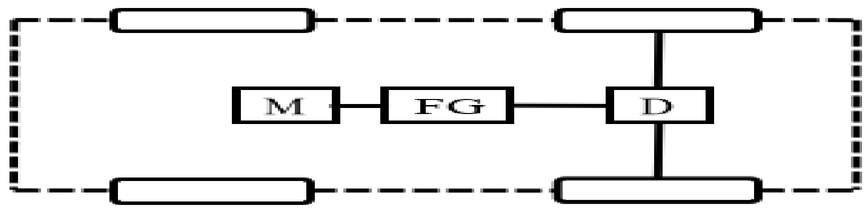
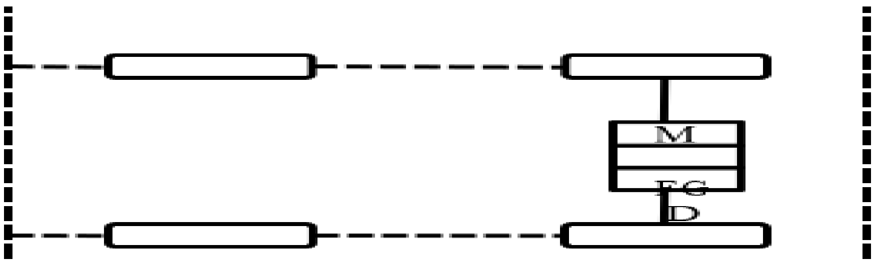
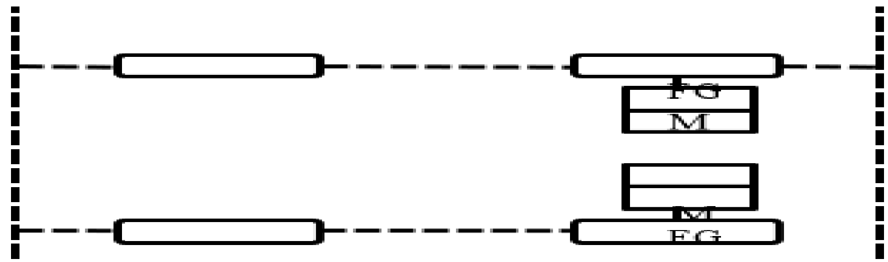


Figure 3b: EV configuration without clutch and gearbo [1]





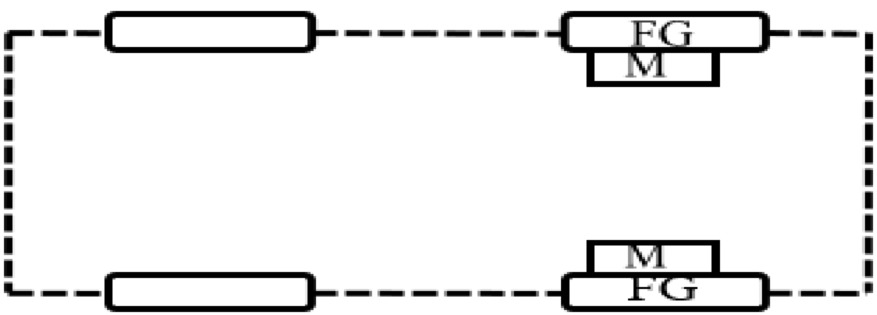


Figure 3e:EV configuration with in wheel motor and mechanical gear [1]

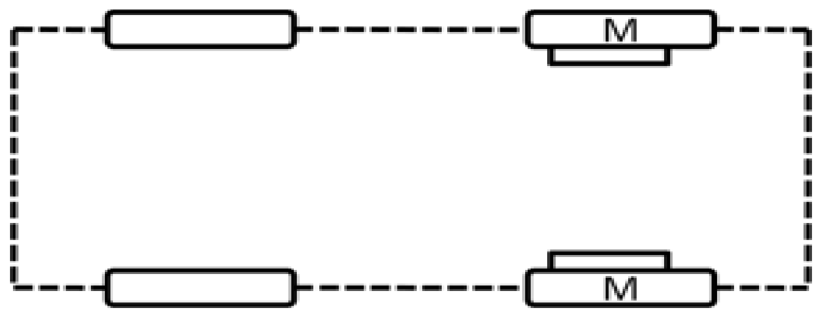


Figure 3f:EV configuration with in wheel motor and no mechanical gear [1]

C: Clutch
D: Differential
FG: Fixed gearing

GB: Gearbox
EM: Electric motor

Electric Vehicle (EV) Drivetrain Alternatives Based on Power Source Configuration:

Besides the variations in electric propulsion, there are other EV configurations due to variations in energy sources. There are five configurations possible and they are:

- **Configuration 1:** It is a simple battery powered configuration, **Figure 4a**. The battery may be distributed around the vehicle, packed together at the vehicle back or located beneath the vehicle chassis.
- **Configuration 2:** Instead of two batteries, this design uses two different batteries, **Figure 4b**. One battery is optimized for high specific energy and the other for high specific power.
- **Configuration 3:** The battery is an energy storage device, whereas the fuel cell is an energy generation device. from air.

- **Configuration 4:** 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, **Figure 4d.** In this case a mini reformer is installed in the EV to produce necessary hydrogen gas for the fuelcell.
- **Configuration 5:** In fuel cell and battery combination, the battery is selected to provide high specific power and high-energy receptivity. In this configuration a battery and supercapacitor combination is used as an energy source, **Figure 4e**.

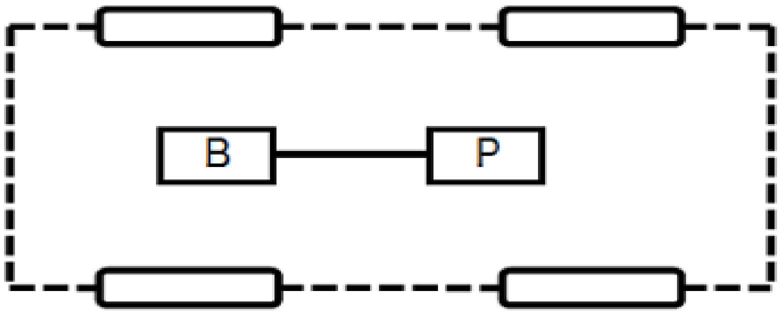


Figure 4a: EV configuration with battery source [1]

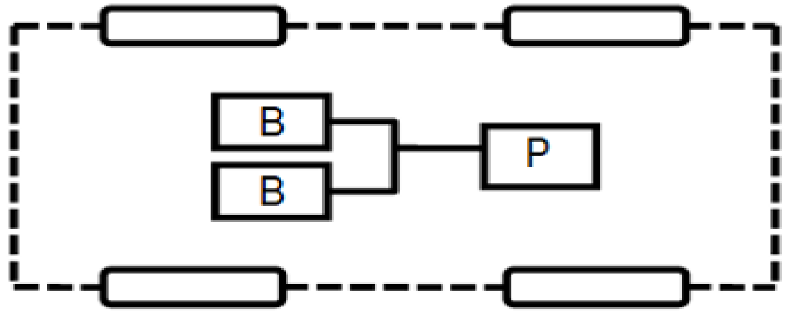


Figure 4b: EV configuration with two battery sources [1]

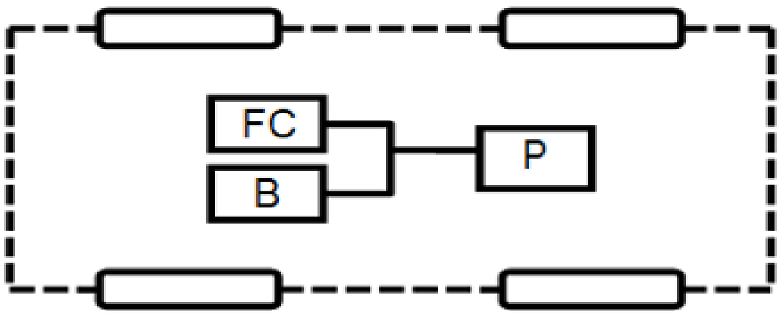


Figure 4c: EV configuration with battery and fuel cell sources [1]

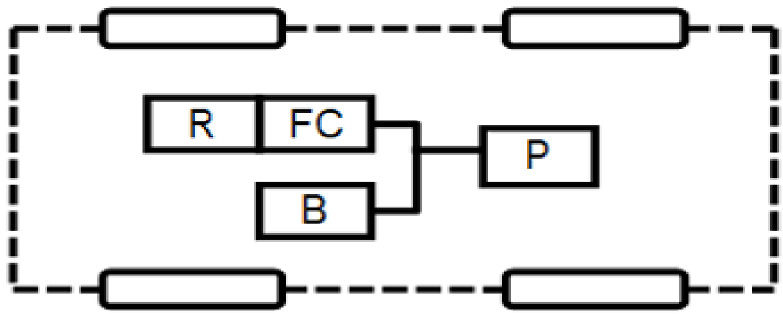


Figure 4d: EV configuration with multiple energy sources [1]

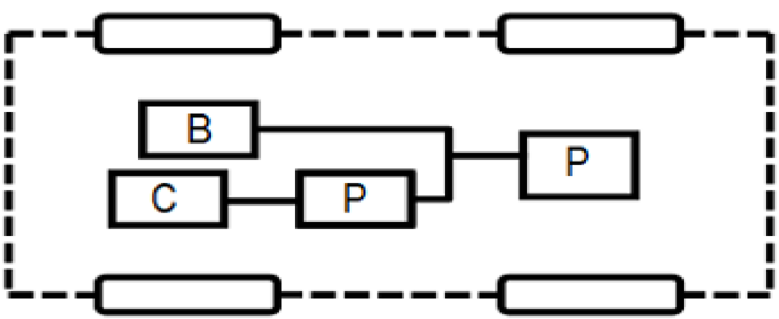


Figure 4e: EV configuration with battery and capacitors sources [1]

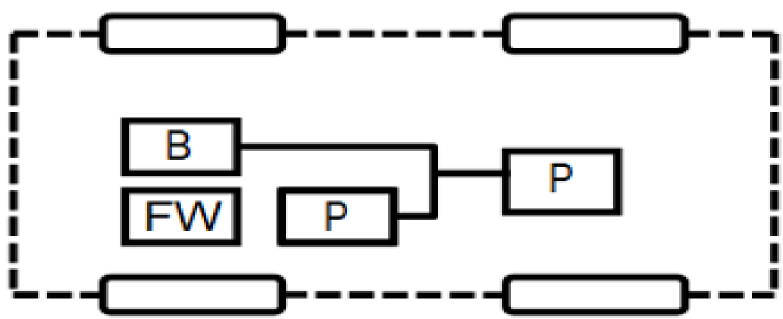


Figure 4f: EV configuration with battery and flywheel sources [1]

Considerations of EMs used in EVs:

The requirements of EMs used in EVs are:

- Frequent start/stop
- High rate of acceleration and deceleration
- High torque low speed hill climbing
- Low torque cruising
- Very wide speed range of operation

The EMs for EVs are unique and their major differences with respect to industrial motors in load requirement, performance specification and operating environment are as follows:

- EV motors need to produce the maximum torque that is four to five times of the rated torque for acceleration and hill climbing, while industrial motors generally offer the maximum torque that is twice of the rated torque for overload operation
- EV motors need to achieve four to five times the base speed for highway cruising, while industrial motors generally achieve up to twice the base speed for constant power operation

UNIT-III
ELECTRIC MOTORS FOR HYBRID ELECTRIC VEHICLES

- Vehicle propulsion has specific requirements that distinguish stationary and onboard motors. Every kilogram onboard the vehicle represents an increase in structural load.
- This increase structural load results in lower efficiency due to increase in the friction that the vehicle has to overcome. Higher efficiency is equivalent to a reduction in energy demand and hence, reduced battery weight.
- The fundamental requirement for traction motors used in EVs is to generate propulsion torque over a wide speed range. These motors have intrinsically neither nominal speed nor nominal power.

DC MOTOR DRIVES

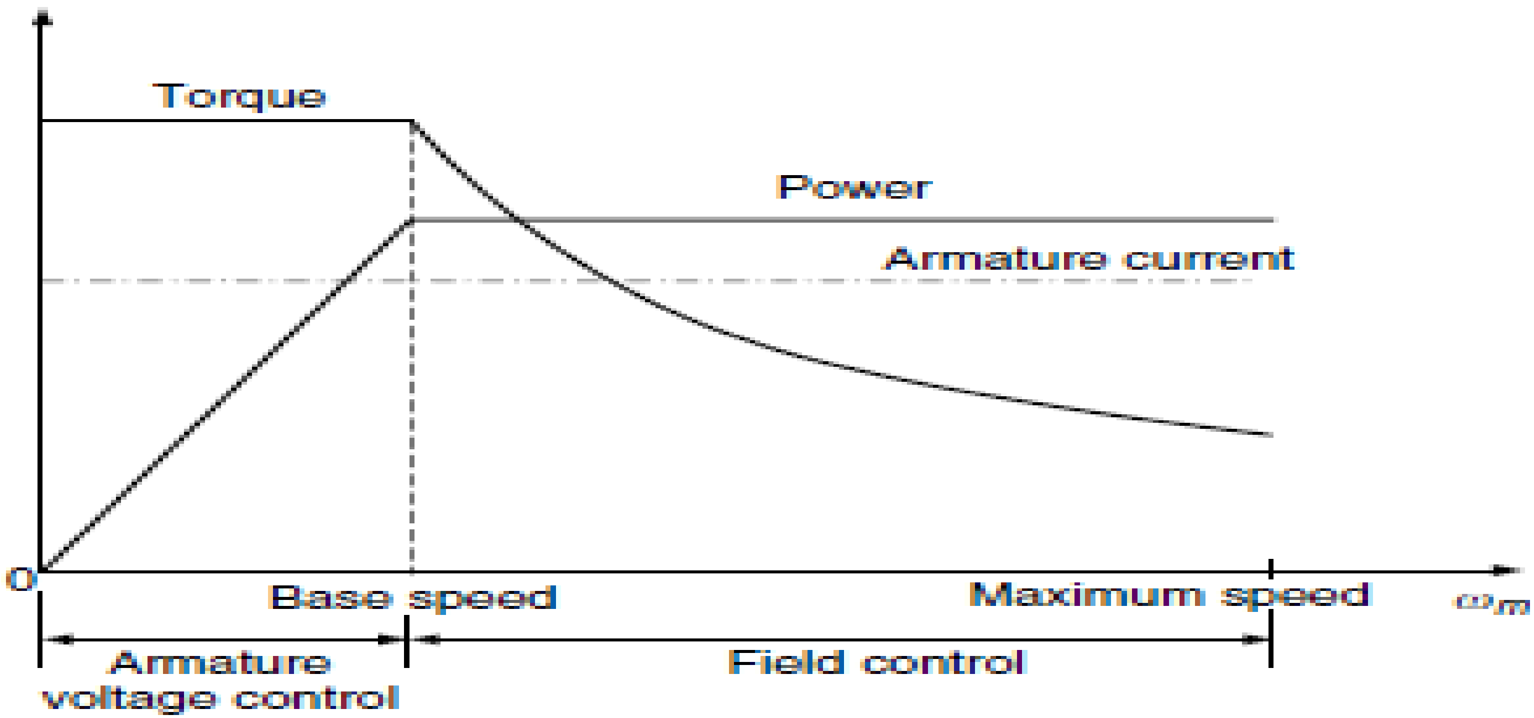
- DC motor drives have been widely used in applications requiring adjustable speed, good speed regulation, and frequent starting, braking and reversing. Various DC motor drives have been widely applied to different electric traction.

COMBINED ARMATURE VOLTAGE AND FIELD CONTROL:

- The independence of armature voltage and field provides more flexible control of the speed and torque than other types of DC motors.

COMBINED ARMATURE VOLTAGE AND FIELD CONTROL:

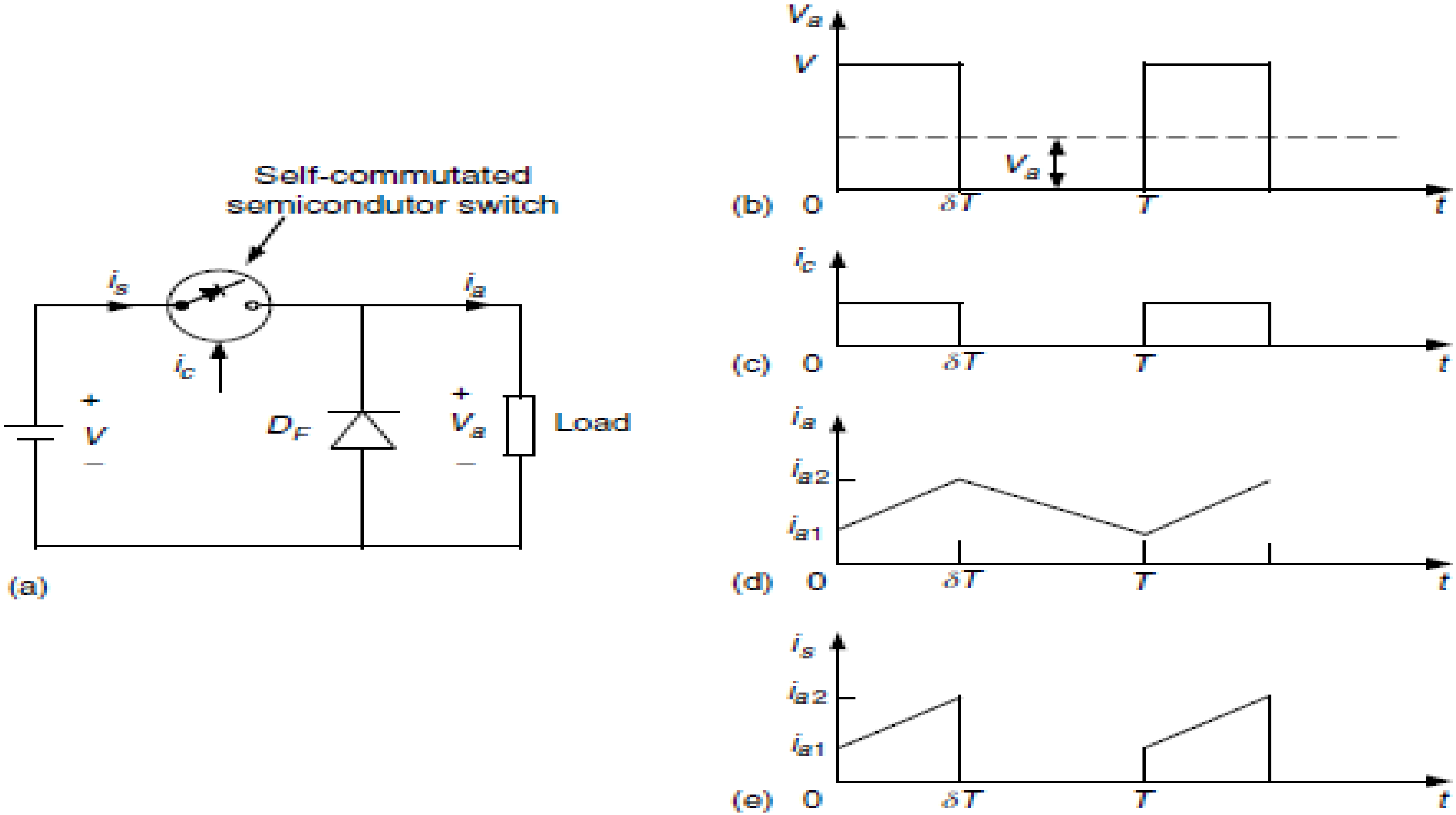
Torque and power limitations in combined armature voltage and field control



CHOPPER CONTROL OF DC MOTORS:

- Choppers are used for the control of DC motors because of a number of advantages such as high efficiency, flexibility in control, light weight, small size, quick response, and regeneration down to very low speeds. Presently, the separately excited DC motors are usually used in traction, due to the control flexibility of armature voltage and field.
- For a DC motor control in open-loop and closed-loop configurations, the chopper offers a number of advantages due to its high operation frequency.

CHOPPER CONTROL OF DC MOTORS:



CHOPPER CONTROL OF DC MOTORS:

- A DC voltage source, *V*, supplies an inductive load through a self-commutated semiconductor switch *S*. The symbol of a self-commutated semiconductor switch has been used because a chopper can be built using any device among thyristors with a forced commutation circuit:
- GTO, power transistor, MOSFET, and IGBT. The diode shows the direction in which the device can carry current. A diode *DF* is connected in parallel with the load.
- The semiconductor switch *S* is operated periodically over a period *T* and remains closed for a time $ton=\delta T$ with $0 \leq \delta \leq 1$. The variable $\delta = ton/T$ is called the duty ratio or duty cycle of a chopper. Figure 6.8also shows the waveform of control signal *ic*. Control signal *ic* will be the base current for a transistor chopper, and a gate current for the GTO of a GTO

CHOPPER CONTROL OF DC MOTORS:

a chopper allows a variable DC voltage to be obtained from a fixed voltage DC source. The switch *S* can be controlled in various ways for varying the duty ratio δ.

The control technologies can be divided into the following categories:

- 1. Time ratio control (TRC).
- 2. Current limit control (CLC).

In TRC, also known as pulse width control, the ratio of on time to chopper period is controlled. The TRC can be further divided as follows:

Constant frequency TRC:

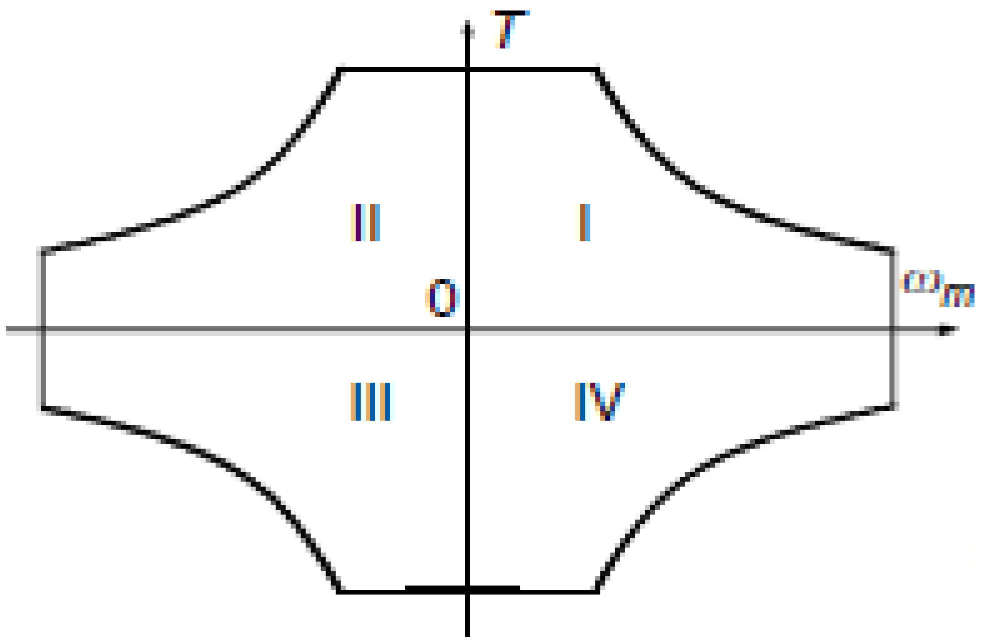
- The chopper period *T* is kept fixed and
- the on period of the switch is varied to control the duty ratio δ.
- Here, δ is varied either by keeping *ton* constant and varying *T* or by varying both *ton* and *T*.

MULTIQUADRANT CONTROL OF CHOPPER-FED DC MOTOR DRIVES:

- The application of DC motors on EVs and HEVs requires the motors to operate in Multiquadarant, including forward motoring, forward braking, backward motoring, and backward braking.
- For vehicles with reverse mechanical gears, two-quadrant operation (forward motoring and forward braking, or quadrant I and quadrant IV) is required. However, for vehicles without reverse mechanical gears, four-quadrant operation is needed.
- Multiquadarant operation of a separately excited DC motor is implemented by controlling the voltage poles and magnitude through power electronics-based choppers.

MULTIQUADRANT CONTROL OF CHOPPER-FED DC MOTOR DRIVES:

Speed–torque profiles of Multiquadarant operation:



TWO-QUADRANT CONTROL OF FORWARD MOTORING AND REGENERATIVEBRAKING:

- A two-quadrant operation consisting of forward motoring and forward regenerative braking requires a chopper capable of giving a positive voltage and current in either direction. This two-quadrant operation can be realized in the following two schemes.

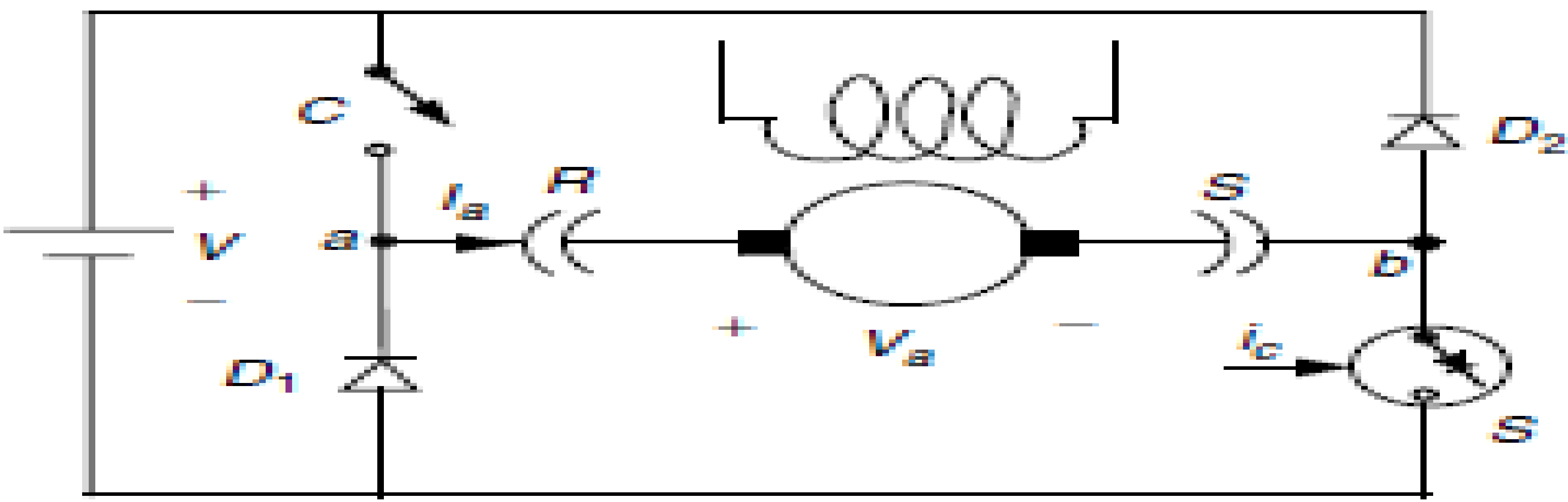
Single Chopper with a Reverse Switch:

- The chopper circuit used for forward motoring and forward regenerative braking , where *S* is a self-commutated semiconductor switch, operated periodically such that it remains closed for a duration of δ*T* and remains open for a duration of (1-δ) *T.C* is the manual switch.
- When *C* is closed and *S* is in operation, the circuit is similar to that of Under these conditions, terminal *a* is positive and terminal *b* is negative. Regenerative braking in the forward direction is obtained when *C* is opened and the armature connection is reversed with the help of the reversing switch *RS*, making terminal *b* positive and terminal *a* negative. During the on-period of the switch *S*, the motor current flows through a path consisting of the motor armature, switch *S*, and diode *D*1.

TWO-QUADRANT CONTROL OF FORWARD MOTORING AND REGENERATIVEBRAKING:

Single Chopper with a Reverse Switch:

Forward motoring and regenerative braking control with a single chopper:



TWO-QUADRANT CONTROL OF FORWARD MOTORING AND REGENERATIVEBRAKING:

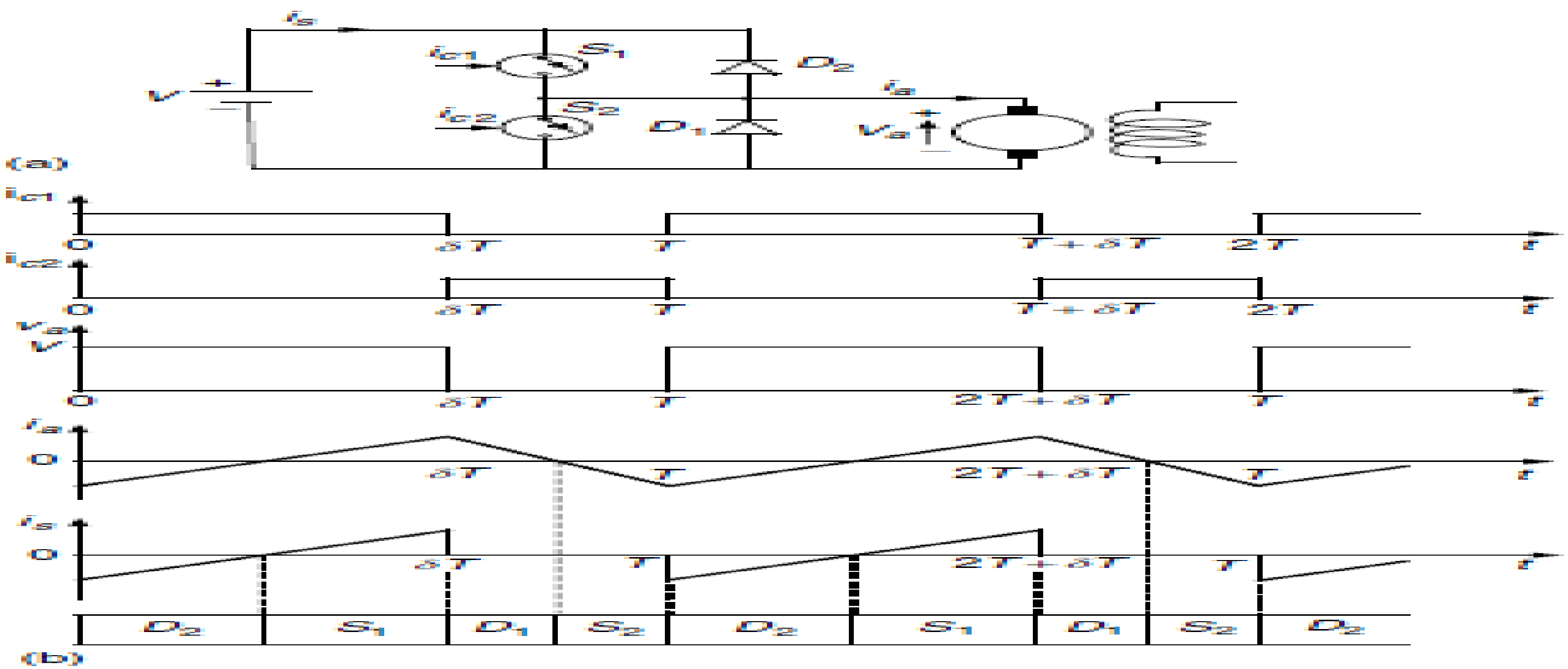
Class C Two-Quadrant Chopper:

- In some applications, a smooth transition from motoring to braking and vice versa is required. For such applications, the class C chopper is used.
- The self-commutated semiconductor switch $S1$ and diode$D1$ constitute one chopper and the self-commutator switch $S2$ and diode$D2$ form another chopper.
- Both the choppers are controlled simultaneously, both for motoring and regenerative braking. The switches $S1$ and $S2$are closed alternately. In the chopping period T, $S1$ is kept on for a duration δT, and $S2$ is kept on from δT to T.
- To avoid a direct, short-circuit across the source, care is taken to ensure that $S1$ and $S2$ do not conduct at the same time. This is generally achieved by providing some delay between the turn off of one switch and the turn on of another switch.

TWO-QUADRANT CONTROL OF FORWARD MOTORING AND REGENERATIVEBRAKING:

Class C Two-Quadrant Chopper:

Forward motoring and regenerative braking control using class C two-quadrant chopper:(a) chopper circuit and (b) waveforms

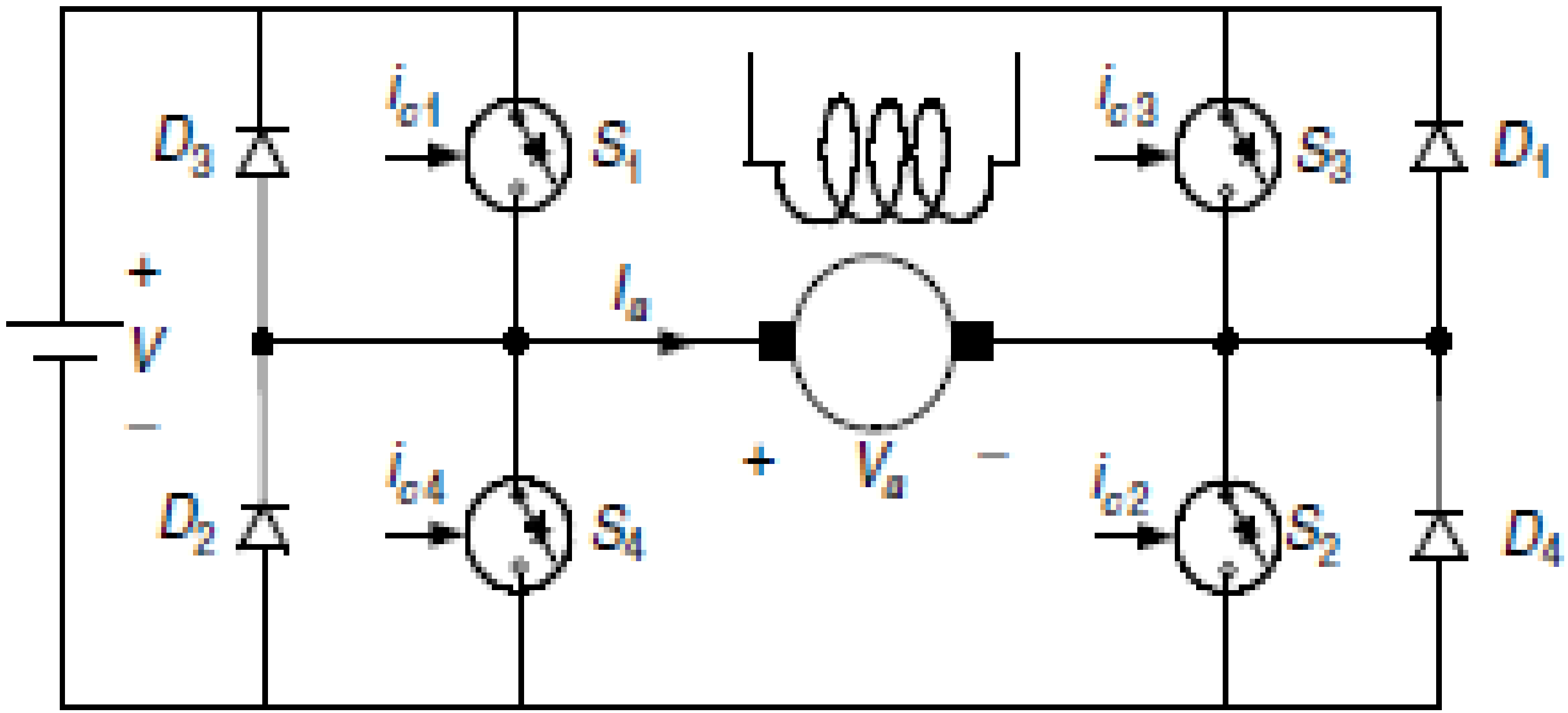


FOUR-QUADRANT OPERATION:

- which is referred to as a class E chopper. In this chopper, if *S*2 is kept closed continuously and *S*1 and *S*4 are controlled, a two-quadrant chopper is obtained, which provides positive terminal voltage (positive speed) and the armature current in either direction (positive or negative torque), giving a motor control in quadrants I and IV.
- Now if *S*3 is kept closed continuously and *S*1 and *S*4 are controlled, one obtains a two-quadrant chopper, which can supply a variable negative terminal voltage (negative speed) and the armature current can be in either direction (positive or negative torque), giving a motor control in quadrants II and III.
- This control method has the following features: the utilization factor of the switches is low due to the asymmetry in the circuit operation. Switches *S*3 and*S*2 should remain on for a long period.

FOUR-QUADRANT OPERATION:

Class E four-quadrant chopper:

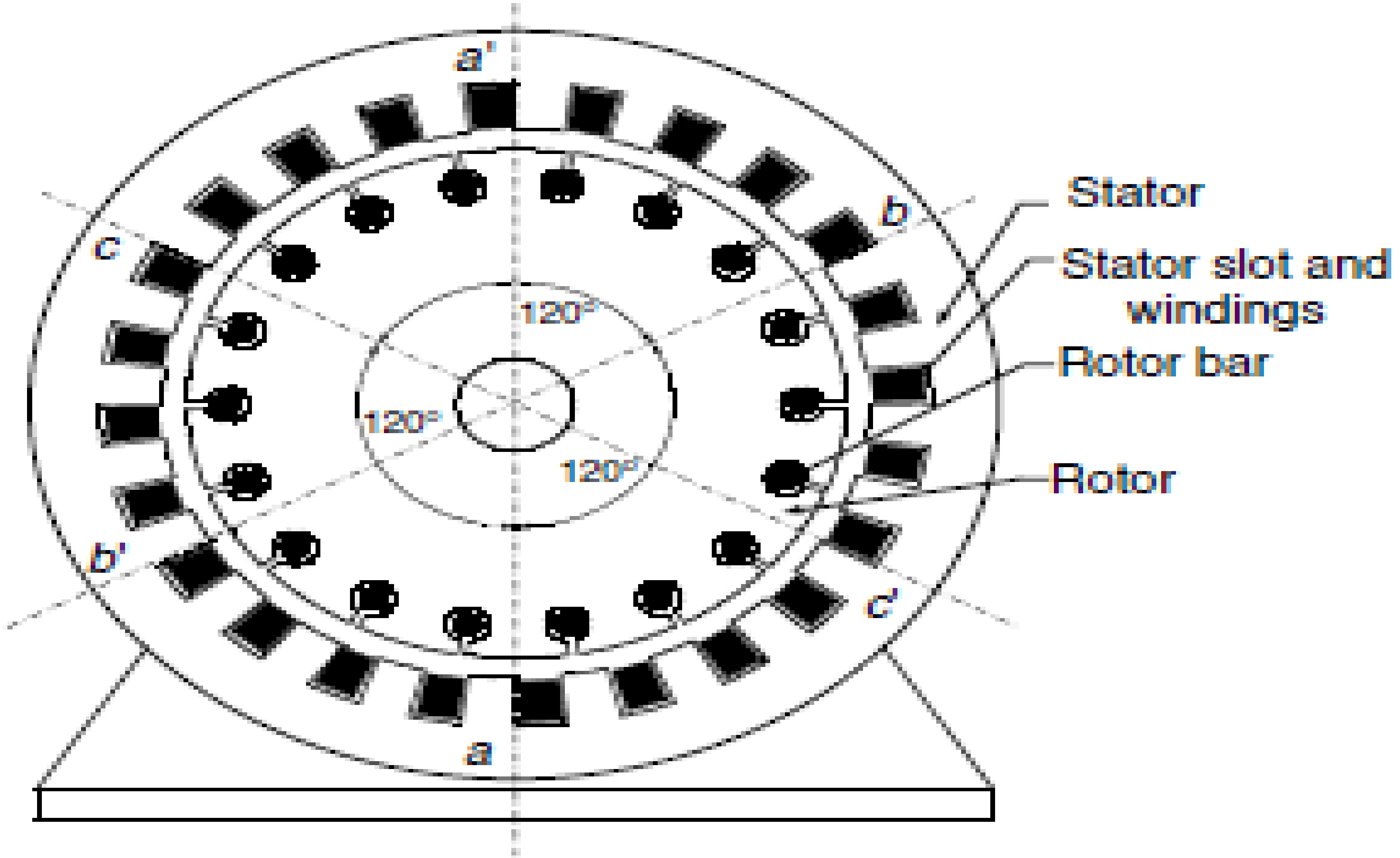


INDUCTION MOTOR DRIVES

- Commutator fewer 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 commutator less 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 HEVapplications.
- 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.
- Hence, squirrel-cage induction motors are loosely termed as induction motors A cross section of a two-pole induction motor is shown in Figure 1. Slots in the inner periphery of the stator are inserted with three phase windings, a–a', b–b', and c–c'.

INDUCTION MOTOR DRIVES

- Cross-section of an induction motor:



Constant Volt/Hertz Control:

- For traction application, the torque–speed characteristic of an induction motor can be varied by simultaneously controlling the voltage and frequency, which is known as constant volt/hertz control.

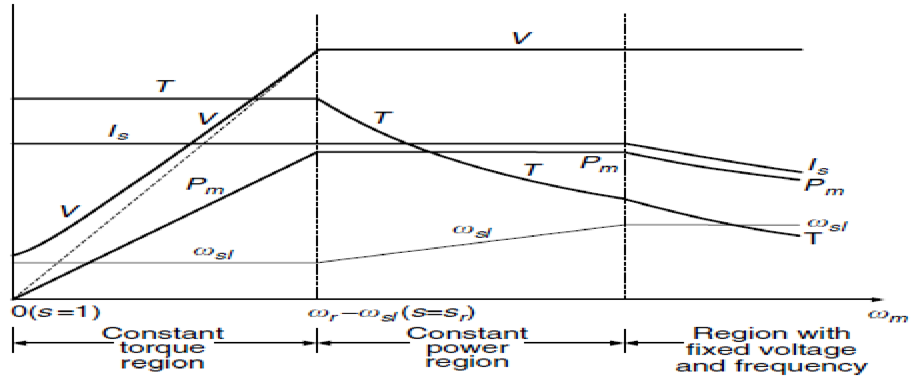
$$I_{mr} = \frac{E}{X_m} = \frac{E_{rated}}{\omega_r L_m},$$

- By emulating a DC motor at low speed, the flux may be kept constant. According to the field current *Im* should be kept constant and equal to its ratedvalue That is,

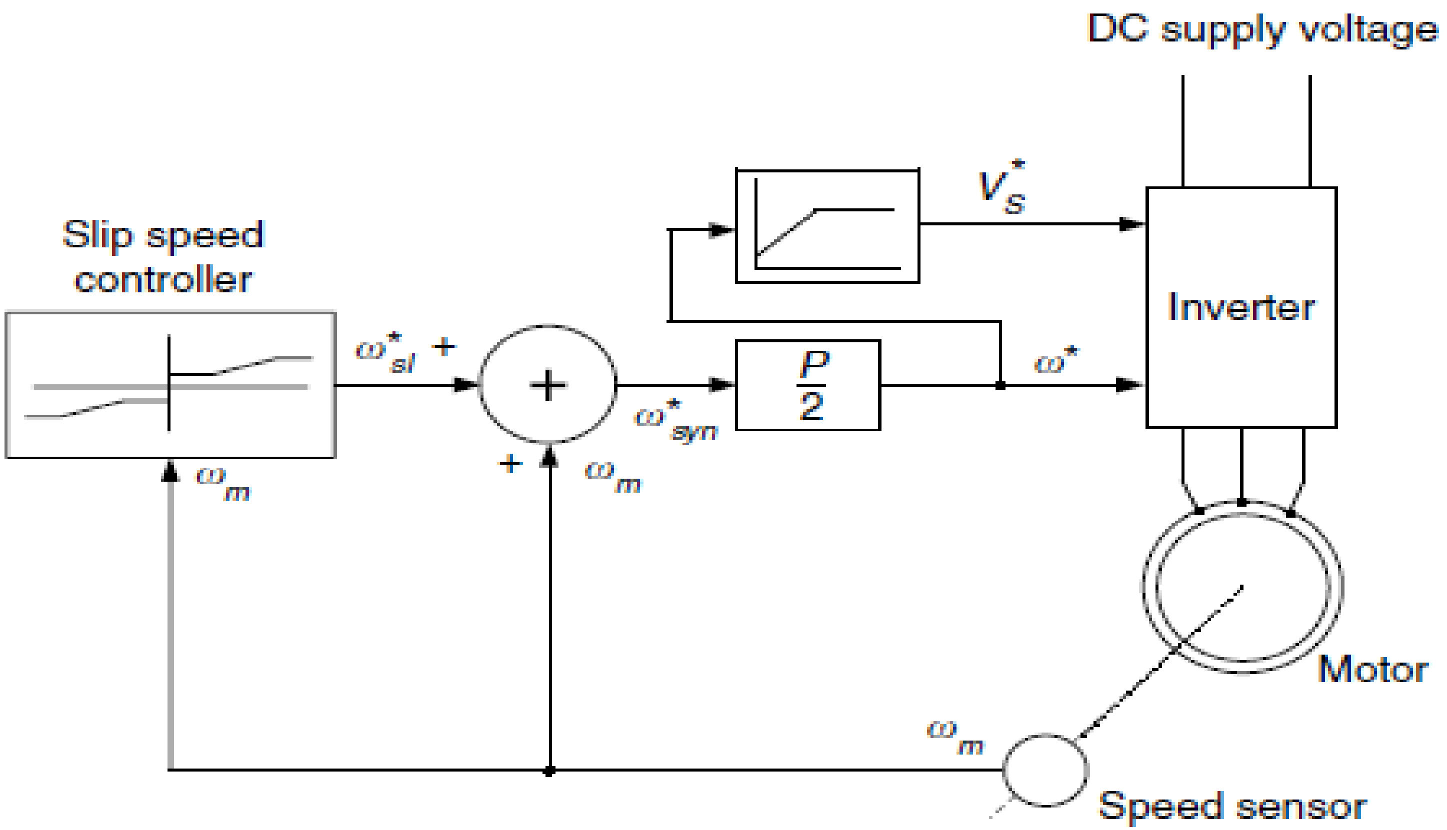
- where *Imr* is the rated field current, and *Erated* and *ωr* are the rated mmf and frequency of the stator, respectively. To maintain the flux at constant, *E*/ω should be kept constant and equal to *Erated*/*ωr*.
- Ignoring the voltage drop in the stator impedance *Zs* results in a constant *V*/ω until the frequency and voltage reach their rated values. This approach is known as constantvolt/hertz control

Constant Volt/Hertz Control:

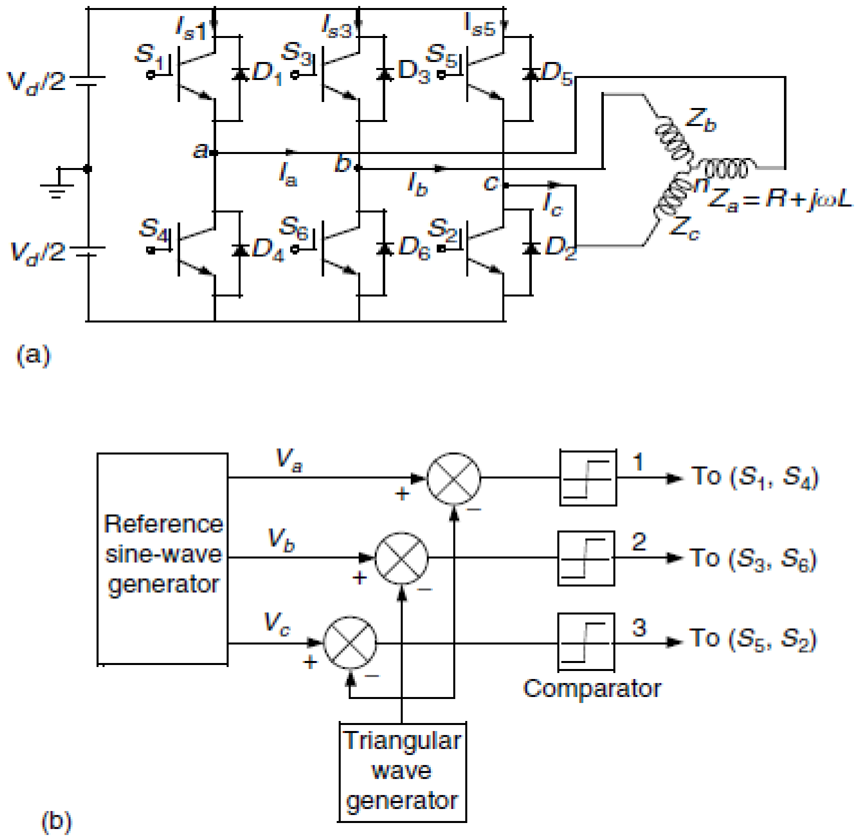
- When motor speed is beyond its rated speed, the voltage reaches its rated value and cannot be increased with the frequency.
- In this case, the voltage is fixed to its rated value and the frequency continuously increases with the motor speed.
- The motor goes into the field weakening operation. The slip *s*is fixed to its rated value corresponding to the rated frequency, and the slip speed *ωsl* increases linearly with motor speed.
- This control approach results in constant power operation as shown in Figure



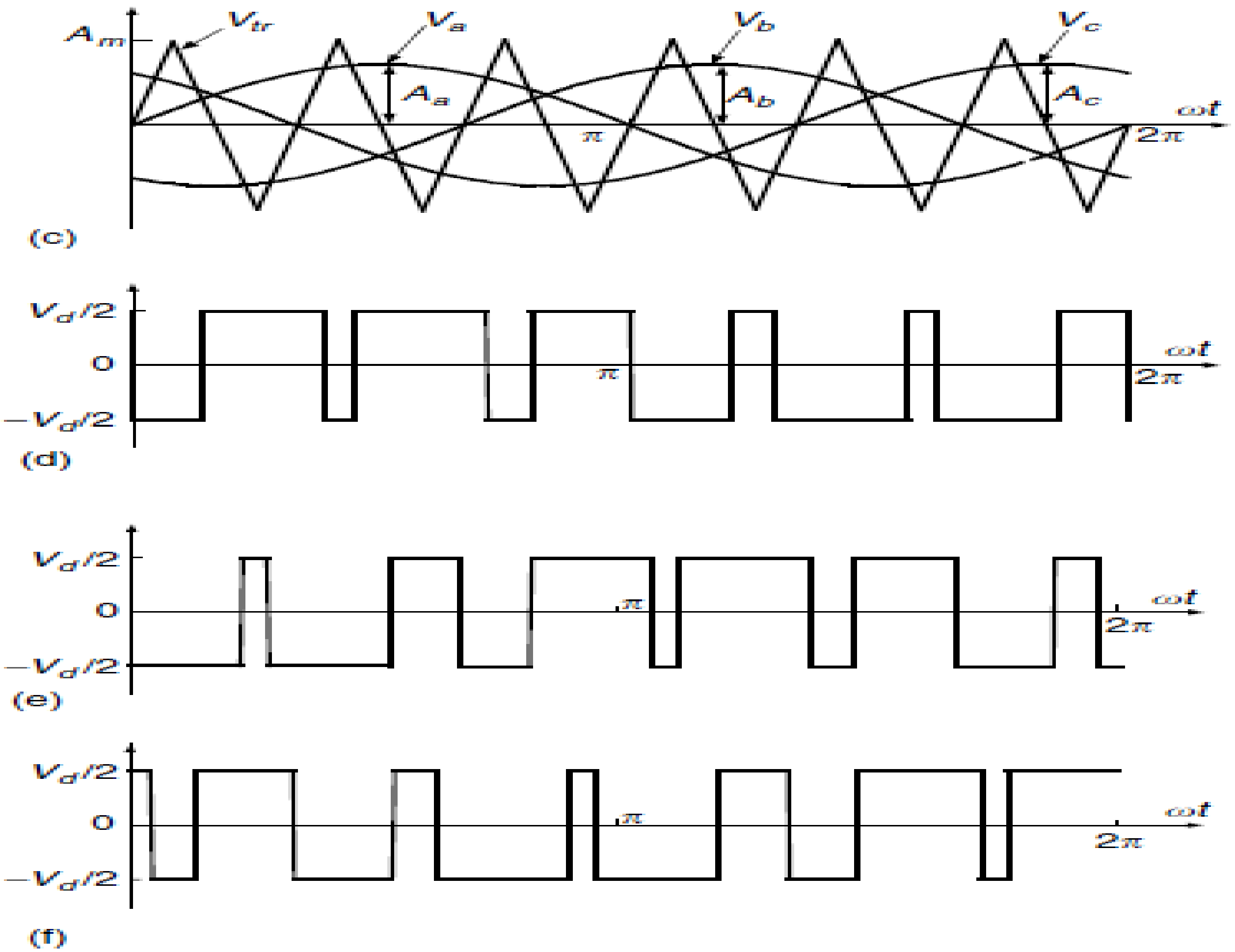
Constant Volt/Hertz Control:



Power Electronic Control:



Power Electronic Control:



Power Electronic Control:

- As EV and HEV propulsion, an induction motor drive is usually fed with a DC source (battery, fuel cell, etc.), which has approximately constant terminal voltage.
- Thus, a variable frequency and variable voltage DC/AC inverter is needed to feed the induction motor. The general DC/AC inverter is constituted by power electronic switches and power diodes.
- The commonly used topology of a DC/AC inverter is shown in Figure(a), which has three legs (*S*1 and *S*4, *S*3 and *S*6, and *S*5 and *S*2), feeding phase *a*, phase *b*, and phase *c* of the induction motor, as shown in Figure(a).
- When switches *S*1, *S*3, and *S*5 are closed, *S*4, *S*6, and *S*2 are opened, and phases *a, b*, and *c* are supplied with a positive voltage (*Vd*/2).
- Similarly, when *S*1, *S*3, and *S*5 are opened and *S*4, *S*6, and *S*2 are closed, phases *a, b*, and *c* are supplied with a negative voltage. All the diodes provide a path for the reverse current of each phase.
- For constant volt/hertz control of an induction motor, sinusoidal pulse width modulation (PWM) is used exclusively.

Power Electronic Control:

- On the other hand, when the reference sinusoidal voltage is smaller than the triangular wave voltage, turn-on signals are sent to the switches *S*1, *S*3, and *S*5 and turn-off signals are sent to *S*4, *S*6, and *S*2.
- The three phases of the induction motor then have a negative voltage. The voltages of the three phases are shown in Figure (d) to (f).

$$m = \frac{A}{A_m},$$

- The frequency of the fundamental component of the motor terminal voltage is the same as that of the reference sinusoidal voltage.

$$V_f = \frac{mV_d}{2\sqrt{2}}.$$

- Hence, the frequency of the motor voltage can be changed by the frequency of the that of the triangular carrier wave, *m*, is called the modulation index.

PMMC MOTORS

By using high energy magnets such as rare earth-based magnets, a PM machine drive can be designed with high power density, high speed and high operation efficiency. These advantages are attractive for their application in EVs and HEVs.

- **The major advantages of PM machines are:**
  - ***High efficiency***: The PM machines have a very high efficiency due to the use of PMs for excitation which consume no power. Moreover, the absence of mechanical commutators and brushes results in low mechanical friction losses.
  - ***High Power density***: The use of high energy density magnets has allowed achieving very high flux densities in the PM machines. As a result of high flux densities, high torque can be produced from a given volume of motor compared to other motors of same volume.

PMMC MOTORS

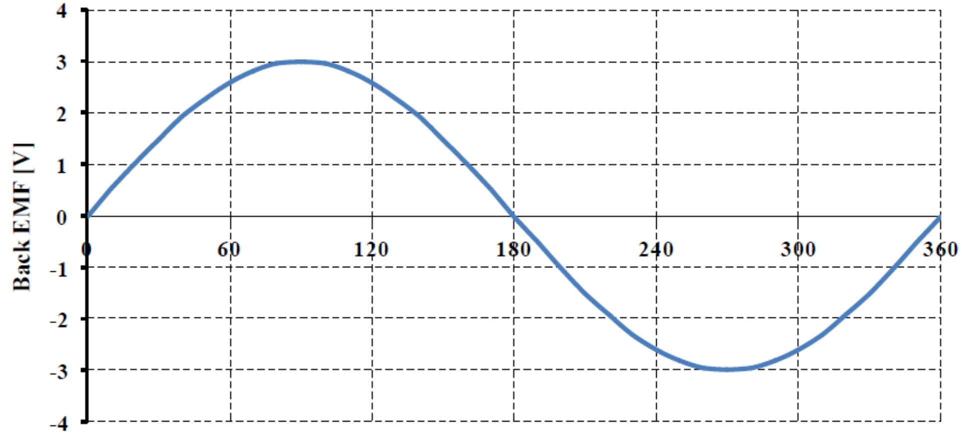


Figure 1a: Sinusoidal back emf

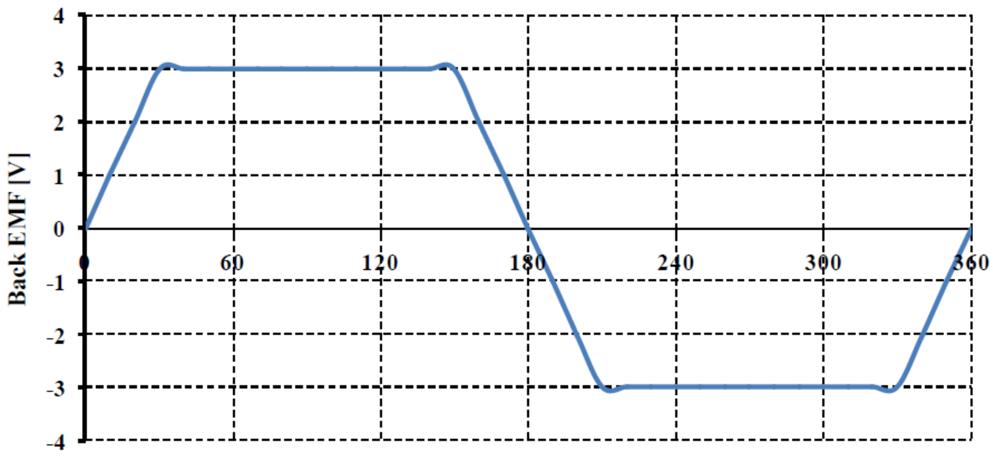


Figure 1b: Trapezoidal back emf

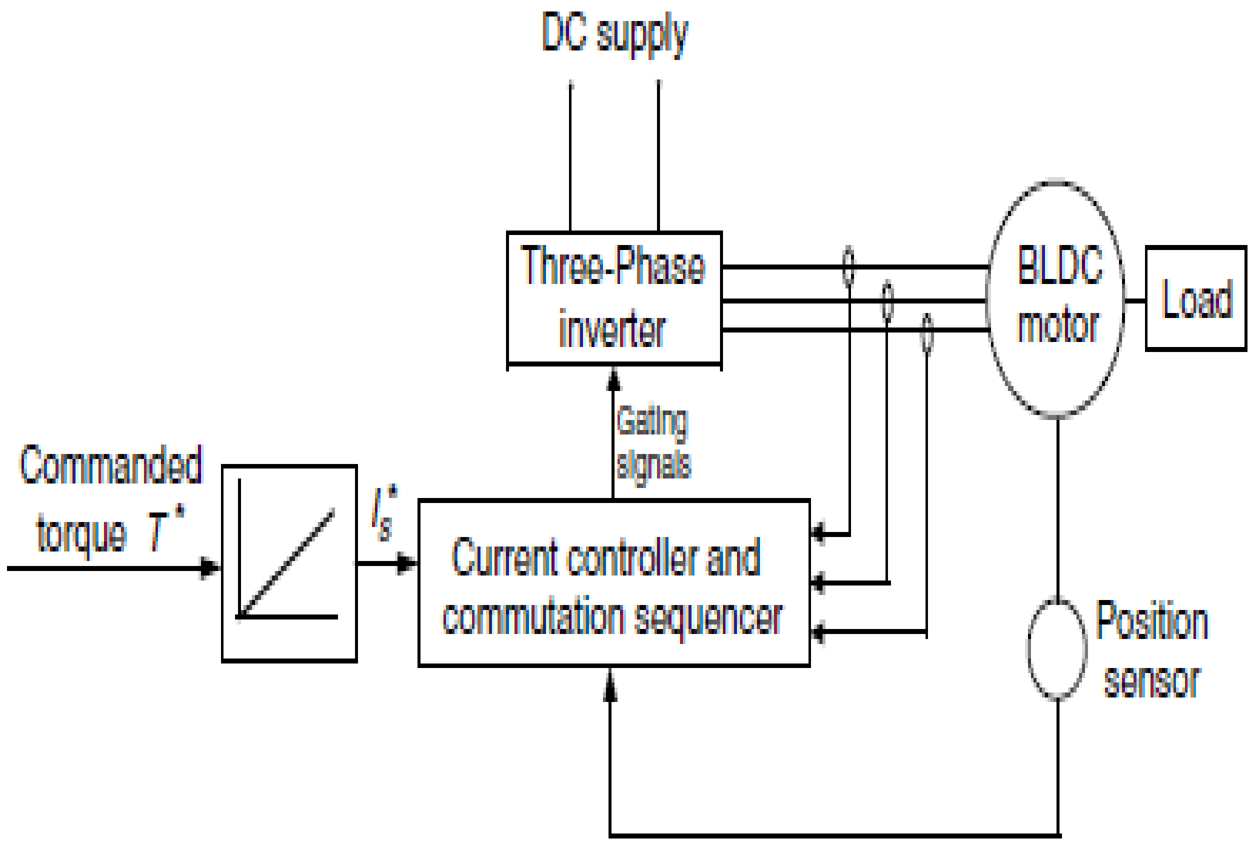
CONTROL STRATEGIES OF PM MACHINES:

There are various control strategies and depending on the application a suitable strategy can be chosen. For example, a mutual flux air gap linkages control gives a smooth transition to flux weakening above the base speed. Similarly, a maximum efficiency control is suitable for applications where energy saving is important such as hybrid and electric vehicles. The most commonly used control strategies are:

- Constant torque angle control
- Unity power factor control
- Constant mutual air gap flux linkages control
- Angle control of air gap flux and current phasors
- Optimum torque per ampere control
- Constant loss based maximum torque speed boundary control
- Minim loss or maximum efficiency control.
- The control strategies marked in bold are discussed in the following sections.

PMMC MOTORS

Control of BLDC Motor Drives:



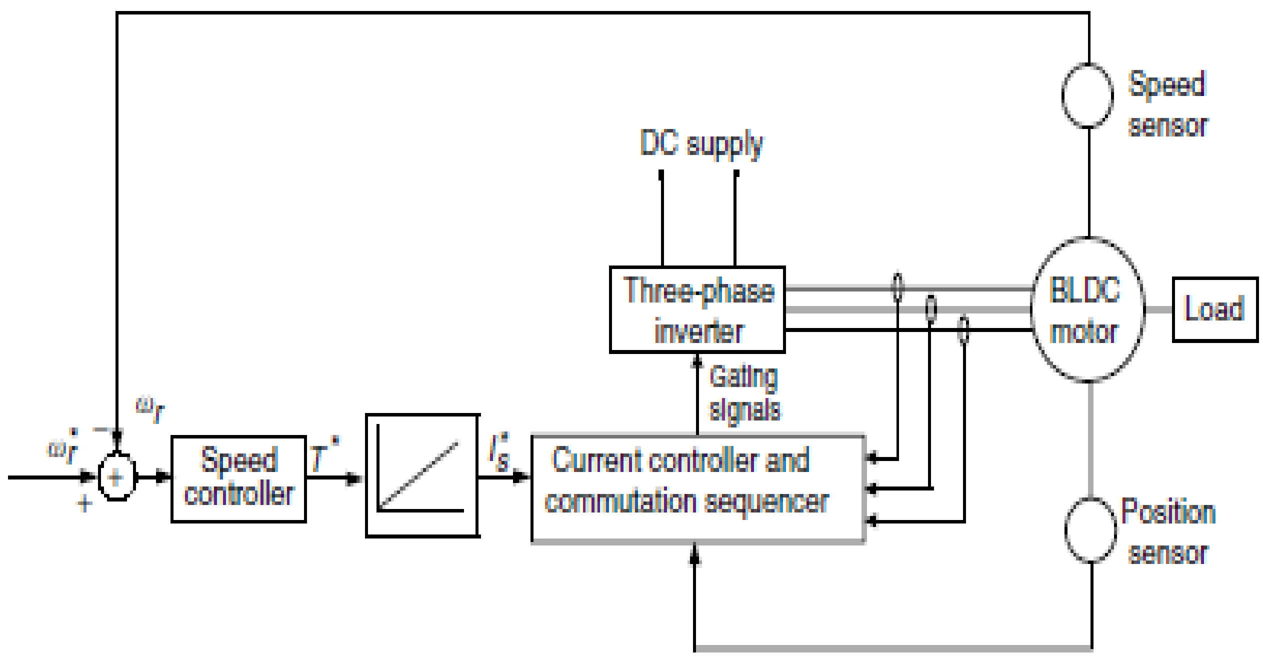
PMMC MOTORS

Control of BLDC Motor Drives:

- torque desired by the driver and commanded through the accelerator and brake pedals. Thus, torque control is the basic requirement.
- Figure shows a block diagram of a torque control scheme for a BLDC motor drive. The desired current *I** is derived from the commanded torque *T** through a torque controller.
- The current controller and commutation sequencer receive the desired current *I** position information from the position sensors, and perhaps the current feedback through current transducers, and then produces gating signals.
- These gating signals are sent to the three-phase inverter(power converter) to produce the phase current desired by the BLDC machine. In traction application, speed control may be required, cruising control
- operation, for example . Many high-performance applications include current feedback for torque control.
- At the minimum, a DC bus current feedback is required to protect the drive and machine from overcurrent's.
- The controller blocks, “speed controller” may be any type of classical controller such as a PI controller, or a more advanced controller such as an artificial intelligence control.
- The “current controller and commutation sequencer” provides the properly sequenced gating signals to the “three phase inverter” while comparing sensed currents to a reference to maintain a constant peak current control by hysteresis (current chopping) or with avoltage source (PWM)-type current control.
- Using position information, thecommutation sequencer causes the inverter to “electronically commutate, ”acting as the mechanical commutator of a conventional DC machine.
- The commutation angle associated with a brush-less motor is normally set so that the motor will commutate around the peak of the torque angle curve.
- Considering a three-phase motor, connected in delta or wye, commutation occurs at electrical angles, which are 30º (electrical) from the peaks of the torque–angle curves

Control of BLDC Motor Drives:

Extension of Speed Technology:



Control of BLDC Motor Drives:

Extension of Speed Technology:

- PM BLDC machines inherently have a short constant power range due to their rather limited field weakening capability.
- This is a result of the presence of the PM field, which can only be weakened through the production of a stator field component that opposes the rotor magnetic field. The speed ratio, *x*, is usually less than 2.
- Recently, the use of additional field windings to extend the speed range of PM BLDC motors has been developed.
- The key is to control the field current in such a way that the air gap field provided by PMs can be weakened during high-speed constant-power operation.
- Due to the presence of both PMs and the field windings, these motors are called PM hybrid motors.
- The PM hybrid motor can achieve a speed ratio of around 4. The optimal efficiency profiles of a PM hybrid motor drive.
- However, the PM hybrid motors have the drawback of a relatively complex structure. The speed ratio is still not enough to meet the vehicle performance requirement, especially in an off-road vehicle. Thus, a multi-gear transmission is required.

Control of BLDC Motor Drives:
Sensor less Techniques:

- The operation of the BLDC motor drives relies mostly on position sensors for obtaining the rotor position information so as to perform the turn on or turn off of each phase properly.
- The position sensor is usually either a three-element Hall-effect sensor or an optical encoder. These position sensors are high-cost, fragile elements.
- Thus, their presence not only enhances the cost of the motor drive but also seriously lowers its reliability and limits its application in some environments, such as a military one.
- Position sensor less technology can effectively continue the operation of the system in case the position sensors lose their function. This is crucial in some applications, such as in military vehicles
- Several sensor less technologies have been developed. The majority of them are based on voltage, current, and back EMF detection. These techniques can be primarily grouped into four categories:

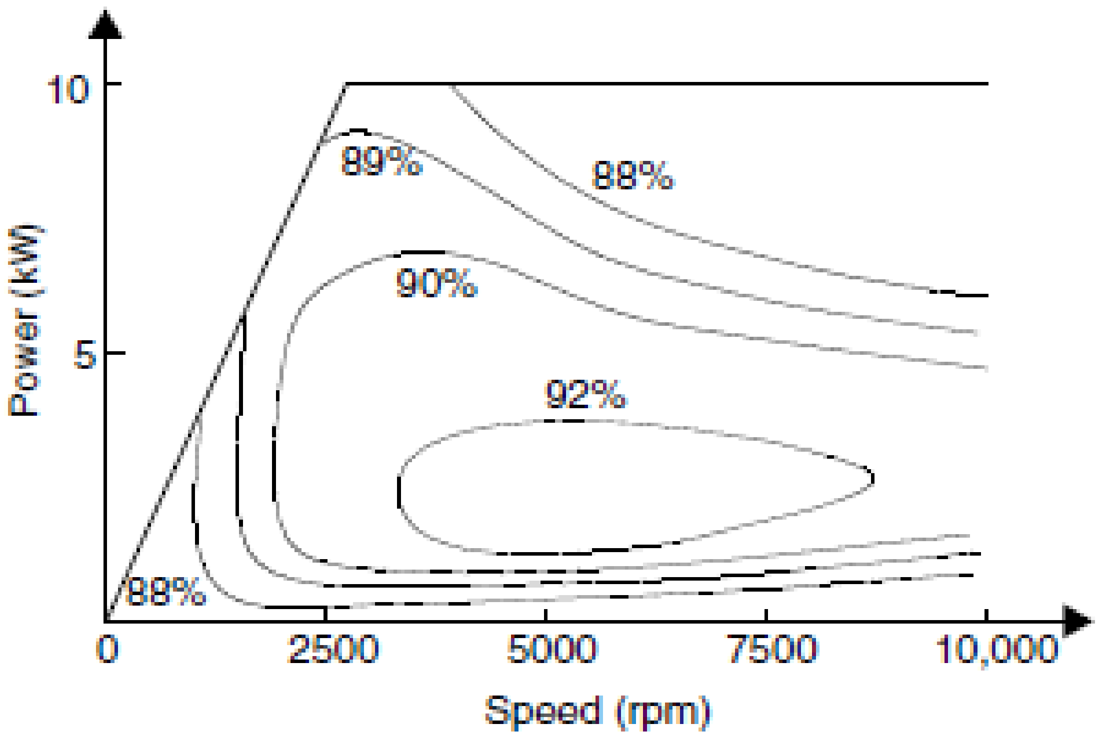
1. Those using measured currents, voltages, fundamental machine equations, and algebraic manipulations
2. Those using observer
3. Those using back EMF methods
4. Those with novel techniques not falling into the previous three categories

PMMC MOTORS

Control of BLDC Motor Drives:

Sensor less Techniques:

Optimal efficiency profiles of a PM hybrid motor drive characteristics:

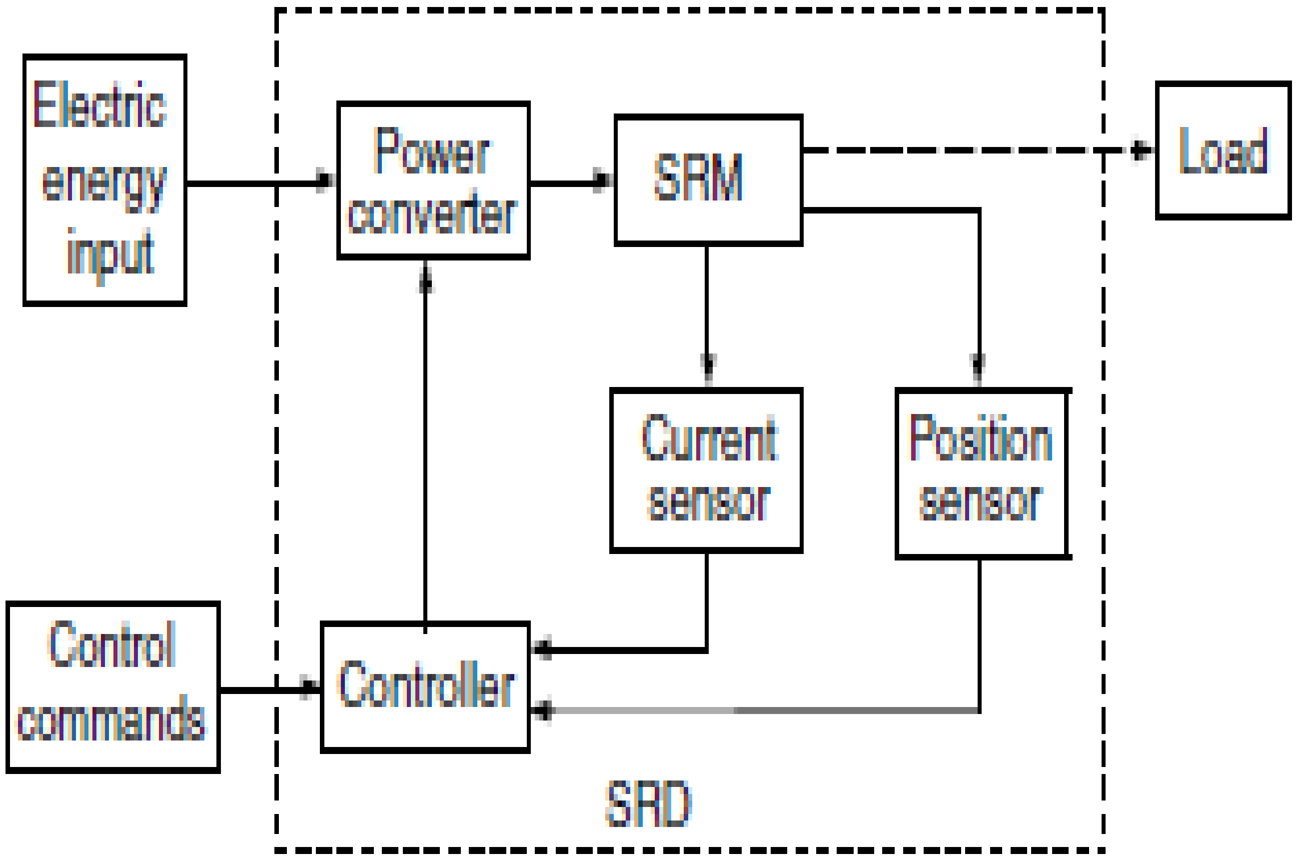


SWITCH RELUCTANCE MOTORS

- The switched reluctance motor (SRM) drive is considered to be an attractive candidate for variable speed motor drives due to its low cost, rugged structure, reliable converter topology, high efficiency over a wide speed range, and simplicity in control.
- These drives are suitable for EVs, electric traction applications, automotive applications, aircraft starter/generator systems, mining drives, washing machines, door actuators, etc.48,50,51The SRM has a simple, rugged, and low-cost structure.
- It has no PM or winding on the rotor. This structure not only reduces the cost of the SRM but also offers high-speed operation capability for this motor. Unlike the induction and PM machines, the SRM is capable of high-speed operation without the concern of mechanical failures that result from the high-level centrifugal force.
- In addition, the inverter of the SRM drive has a reliable topology. The stator windings are connected in series with the upper and lower switches of the inverter.
- A conventional SRM drive system consists of the switched reluctance motor, power inverter, sensors such as voltage, current, and position sensors, and control circuitry such as the DSP controller and its peripherals.
- Through proper control, high performance can be achieved in the SRM drive system. The SRM drive inverter is connected to a DC power supply, which can be derived from the utility lines through a front-end diode rectifier or from batteries.
- The phase windings of the SRM are connected to the power inverter.The control circuit provides a gating signal to the switches of the inverter according to particular control strategies and the signalsfrom various sensors.

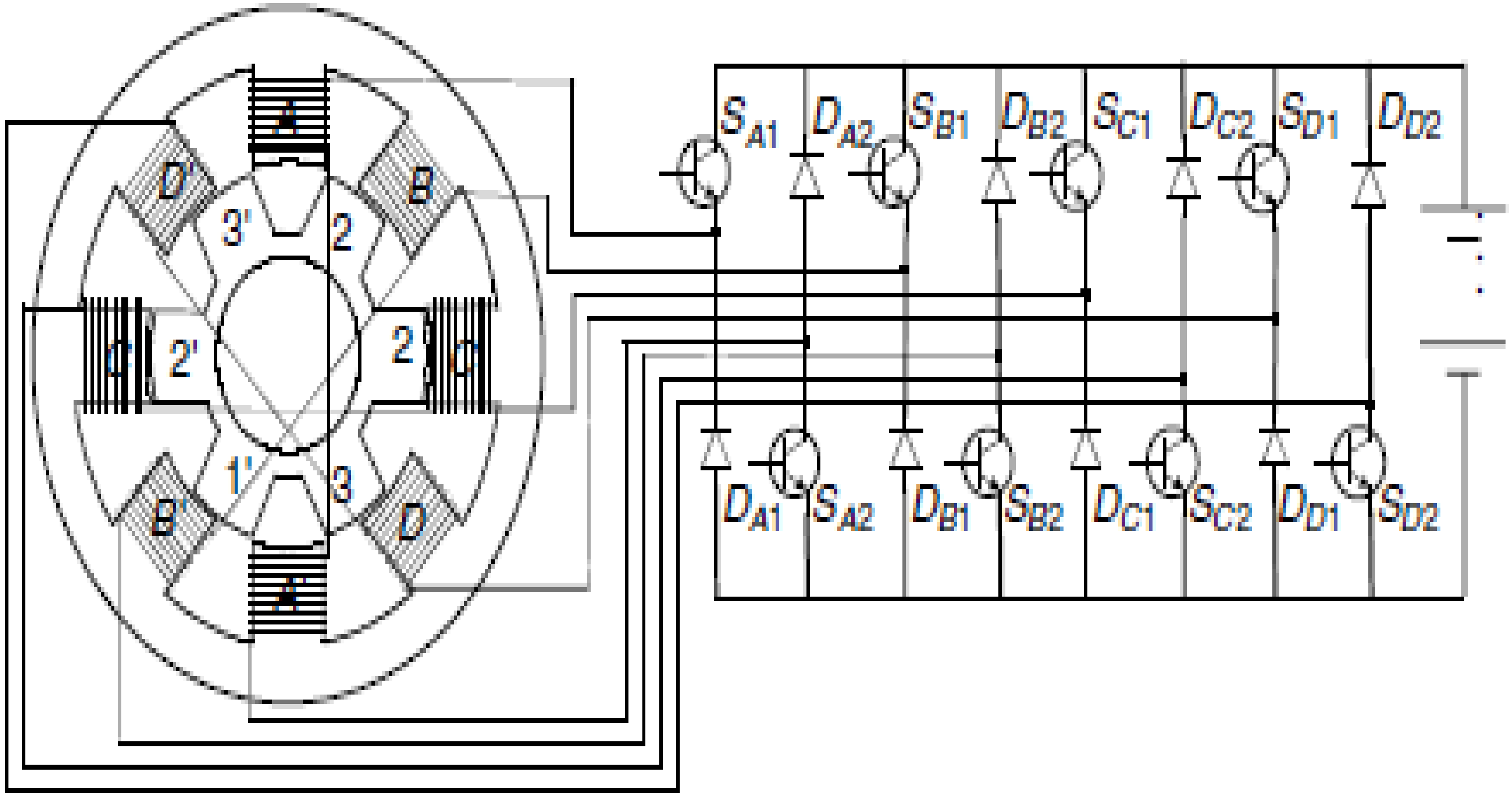
- **Switched Reluctance Motor Drives:**

SRM drive system:



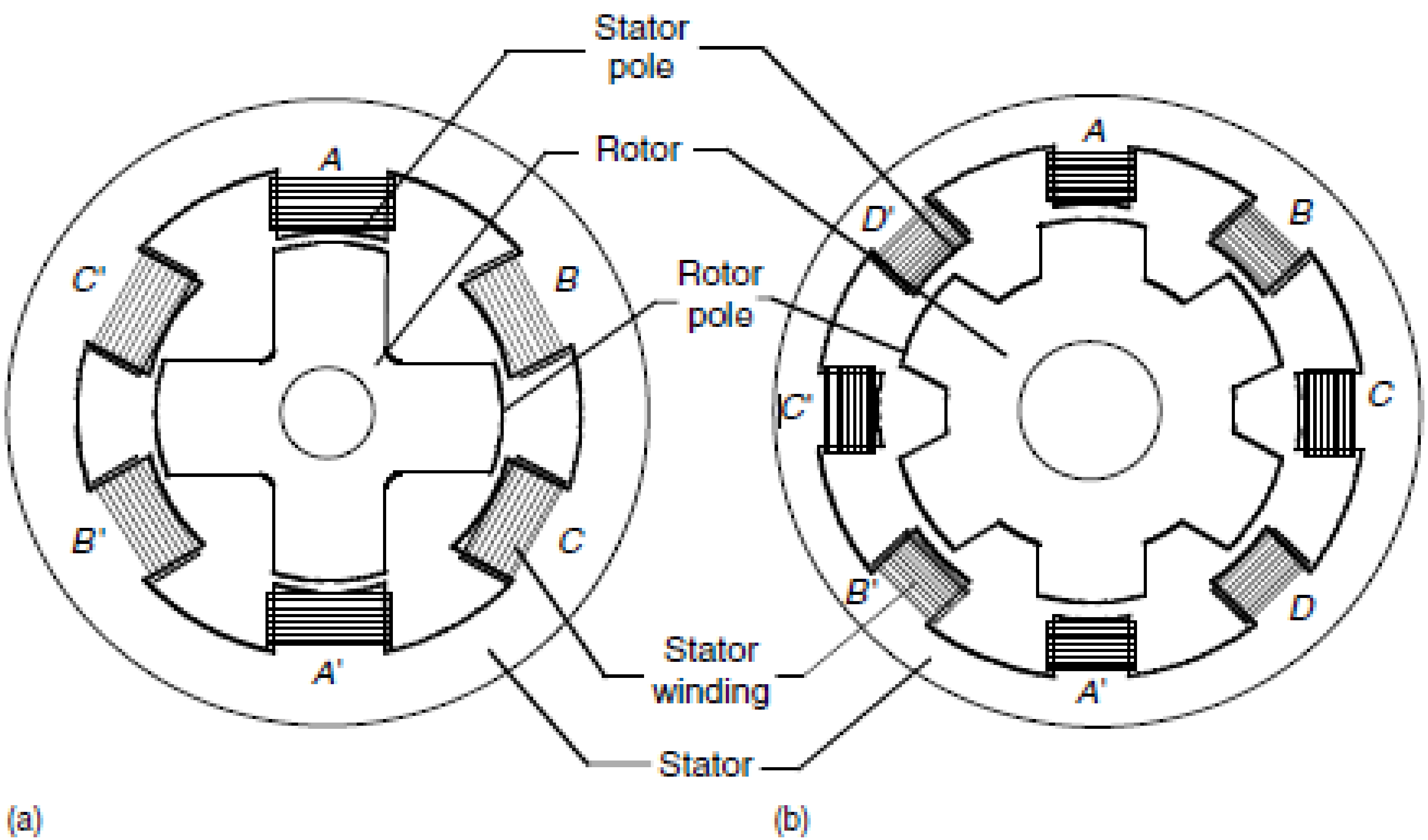
- **Switched Reluctance Motor Drives:**

SRM AND ITS POWER SUPPLY:



- **Switched Reluctance Motor Drives:**

Cross-section of common SRM configurations: (a) a 6/4 SRM and (b) a 8/6 SRM



Switched Reluctance Motor Drives:

Sensor less Control Technique:

- Excitation of the SRM phases needs to be properly synchronized with the rotor position for effective control of speed, torque, and torque pulsation. A shaft position sensor is usually used to provide the rotor position.
- However, these discrete position sensors not only add complexity and cost to the system but also tend to reduce the reliability of the drive system and restrict their application on some specific environment, such as military applications.
- Position sensor less technology can effectively continue the operation of the system, incase the position sensors lose their function.
- the SRM is a function of the angular rotor position. As the rotor moves from the unaligned position toward the aligned position, the phase inductance increases from the minimum value to the maximum value.
- It is obvious that if the phase bulk inductance can be measured and the functional relation between the phase bulk inductance and the rotor position is known, the rotor position can be estimated according to themeasured phase bulk inductance
- Some sensor less techniques do not use the magnetic characteristic and voltage equation of the SRM directly to sense the rotor position. Instead, these sensor less control methods are based on the observer theory or synchronous operation method similar to that applied to conventional ACsynchronous machines

Switched Reluctance Motor Drives:

Sensor less Control Technique:

Generally, the existing sensor less control methods can be classified as:

1.Phase flux linkage-based method

2. Phase inductance-based method

3. Modulated signal injected methods

4. Mutual-induced voltage-based method

5. Observer-based methods.

SWITCH RELUCTANCE MOTORS

Switched Reluctance Motor Drives:

Phase Flux Linkage-Based Method:

- estimate the rotor position. The basic principle of this method is to use the functional relation between the phase flux linkage, phase current, and rotor position for rotor position detection.
- it can be observed that if the flux linkage and phase current are known, the rotor position can be estimated accordingly.
- The problem with this sensor less control method is the inaccurate estimation of the phase flux linkage at low speed.
- At high speed (above the base speed), the phase voltage retains its positive polarity until the phase is turned off. The *V* term dominates in *VRi*, and integration of *VRi* in a relatively short period will not lead to a huge error in flux estimation.
- However, at lows peed (below the base speed), the phase voltage changes its polarity from one hysteresis cycle to the next hysteresis cycle.
- When *VRi* is integrated in a relatively long period, the phase voltage term cancels itself due to the excursions while the *Ri* term retains its polarity during the integration period — and becomes significant after a long time of integration.
- The error in *R* or *i* may lead to a huge error in the flux estimation in this case. Therefore, this sensor less control method is only suitable for the high-speed operation of SRM.

Switched Reluctance Motor Drives:

Phase Inductance-Based Method:

Similar to the phase flux linkage, the phase bulk and incremental inductances are both functions of the phase current and rotor position. Hence, they can also be used for rotor position estimation.

Sensor less Control Based on Phase Bulk Inductance:

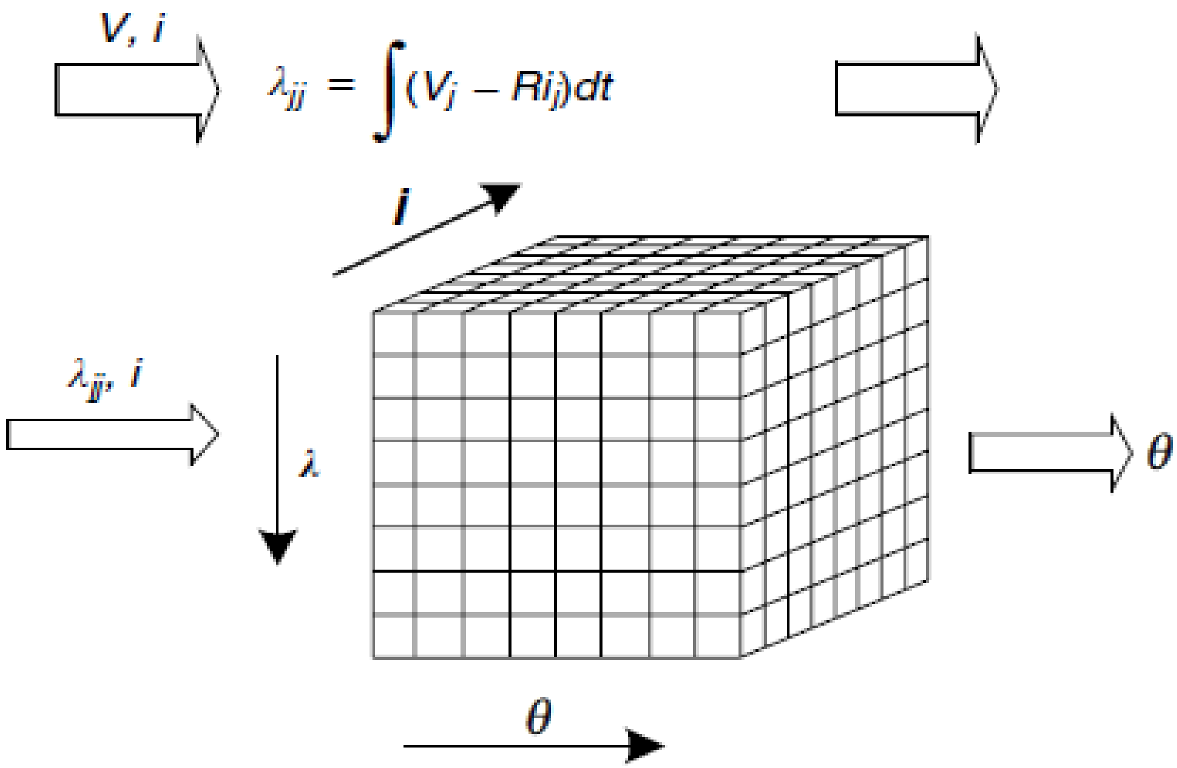
- Using the phase flux linkage obtained as the phase inductance can be obtained as

$$L_{jj} = \frac{\lambda_{jj}}{i_j}.$$

- The estimated phase bulk inductance and measured phase current can be input to a prestored look-up table storing the functional relation between the phase bulk inductance and phase current and rotor position, to find the corresponding rotor position.
- Instead of using a look-up table, one can also use an analytical model to represent the functional relation between phase bulk inductance, phase current, and rotor position Like the flux linkage-based method, since integration of *VRi* is used for phase inductance estimation, this method is only suitable for high-speed operation.
- Some sensor less control methods that can work both at a standstill and at low speed, such as the open-loop method, have to be used to start the SRM and bring the rotor speed to a certain level.
- After the rotor speed has reached a threshold, the phase flux linkage and/or inductance are calculated using the integration method and the rotor position is estimated according to the calculated phase flux linkage and inductance

Switched Reluctance Motor Drives:

- Flux linkage-based rotor position estimation method



Switched Reluctance Motor Drives:

Modulated Signal Injection Methods:

- These methods are to apply a voltage to the idle phase winding and measure the resultant phase current to detect the phase inductance.
- This derived phase inductance will provide the rotor position information. Both an extra low amplitude voltage source and a power converter can be used to apply a voltage to the phase winding.
- When an extra voltage source is used, a sinusoidal voltage is usually used for sensing the phase inductance.
- The phase angle and the amplitude of the resultant phase current contain the phase inductance; hence, the rotor position information can be obtained.
- This is the idea behind the amplitude modulation (AM) and phase modulation (PM)methods. When the power converter is used for sensing purposes, a short period voltage pulse is usually applied to the idle phase and a triangular current is induced in the corresponding phase.
- The changing rate of the phase current contains the phase inductance, and hence the rotor position information. This is the basic idea of the diagnostic pulse-based method

Switched Reluctance Motor Drives:

Mutually Induced Voltage-Based Method:

- The idea of this method is based on measuring the mutually induced voltage in an idle phase, which is either adjacent or opposite to the energized phase of an SRM.
- The mutual voltage in the "off" phase, induced due to the current in the active phase, varies significantly with respect to the rotor position.
- This mutually induced voltage variation can be sensed by a simple electronic circuit.
- If the functional relation between the mutually induced voltage in the inactive phase due to the current in the active phase and the rotor position is known, the rotor position information can be extracted from the mutually measured induced voltage in the inactive phase.
- This method is only suitable for low-speed operation. Furthermore, it is very sensitive to noise since the ratio between induced voltage and system noise is small.

Switched Reluctance Motor Drives:

Observer-Based Methods:

- In this method, state-space equations are used to describe the dynamic behavior of the SRM drive. An observer is then developed based on these nonlinear state-space differenti equations for estimation of the rotor position.
- The input and output of this observer are phase voltage and phase current, respectively. The state variables of this observer are stator flux linkage, rotor position angle, and rotor speed.
- The phase current, flux linkage, rotor position, and rotor speed can be estimated using thi observer. The phase current estimated by this observer is compared to the actual phase current of the SRM, and the resultant current errors are used to adjust the parameters of the observer.
- When the current estimated by the observer matches the actual current, the observer is considered as a correct representation of the dynamic behavior of the actual SRM drive and the rotor position estimated by the observer is used to represent the actual rotor position.
- The main disadvantages of these methods are real-time implementation of complex algorithms, which require a high-speed DSP, and a significant amount of stored data. This increases the cost and speed limitations by the DSP. However, high resolution in detecting rotor position and applicability to whole speed range are some merits of these methods

UNIT-IV
ENERGY STORAGE

Energy storages:

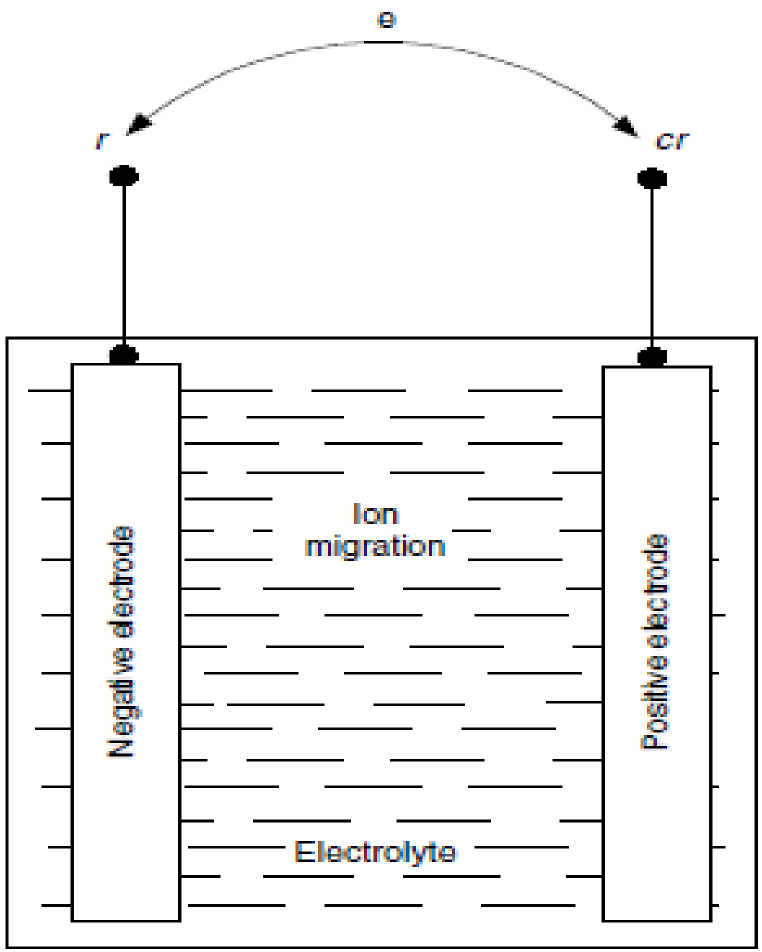
- "Energy storages" are defined in this book as the devices that store energy, deliver energy outside (discharge), and accept energy from outside (charge).
- There are several types of energy storages that have been proposed for electric vehicle (EV) and hybrid electric vehicle (HEV) applications.
-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

ELECTROCHEMICAL BATTERIES

- Electrochemical batteries, more commonly referred to as “batteries,”are electrochemical devices that convert electrical energy into potential chemical energy during charging, and convert chemical energy into electric energy during discharging. A “battery” is composed of several cells stacked together.
- A cell is an independent and complete unit that possesses all the electrochemical properties. Basically, a battery cell consists of three primary elements: two electrodes (positive and negative) immersed into an electrolyte.
- Battery manufacturers usually specify the battery with coulometric capacity(amp-hours), which is defined as the number of amp-hours gained when discharging the battery from a fully charged state until the terminal voltage drops to its cut-off voltage.
- It should be noted that the same battery usually has a different number of amp-hours at different discharging current rates. Generally, the capacity will become smaller with a large discharge current rate.
- Battery manufacturers usually specify a battery with a number of amp-hours along with a current rate.
- Another important parameter of a battery is the state-of-charge (SOC).SOC is defined as the ratio of the remaining capacity to the fully charged capacity.
- With this definition, a fully charged battery has an SOC of100% and a fully discharged battery has an SOC of 0%.
- However, the term “fully discharged” sometimes causes confusion because of the different capacity at different discharge rates and different cut-off voltage.

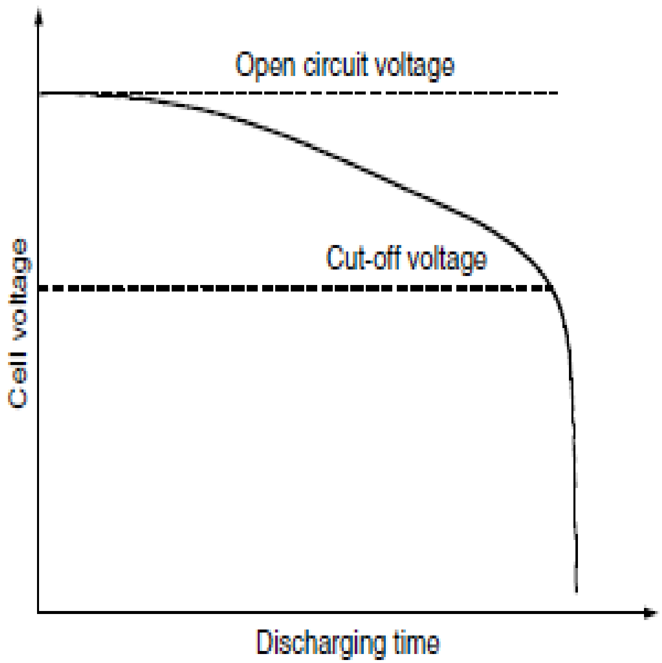
ELECTROCHEMICAL BATTERIES

- A typical electrochemical battery cell:

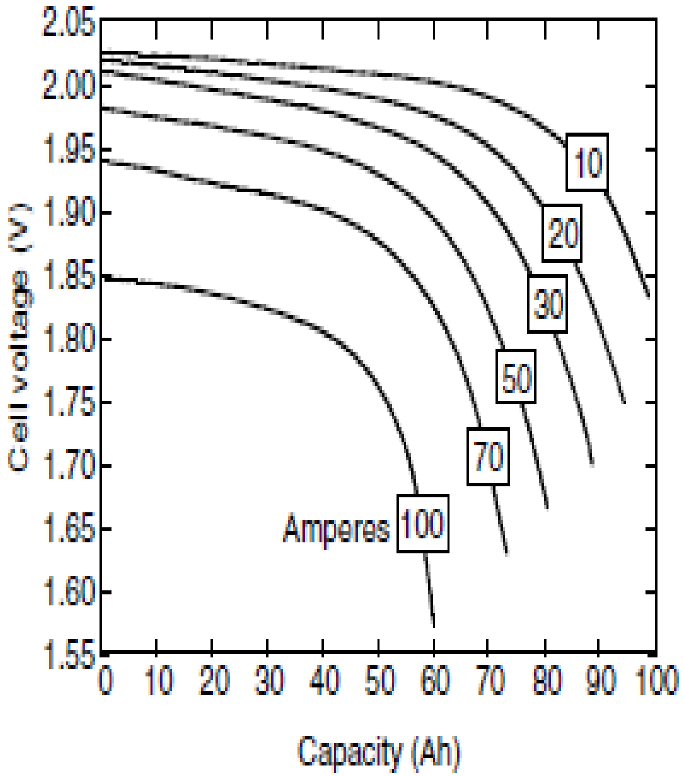


ELECTROCHEMICAL BATTERIES

- Cut-off voltage of a typical battery:



Discharge characteristics of a lead-acid battery:



ELECTROCHEMICAL BATTERIES

- it is the most widespread battery technology in today's automotive applications, the lead-acid battery case is used as an example to explain the operating principle theory of electrochemical batteries. Lead-acid battery uses an aqueous solution of sulfuric acid as the electrolyte.
- The electrodes are made of porous lead (Pb, anode, electrically negative) and porous lead oxide (PbO2, cathode, electrically positive). The processes taking place during discharging are shown in Figure 4.4(a), where lead is consumed and lead sulfate is formed. The chemical reaction on the anode can be written as

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

- This reaction releases two electrons and, thereby, gives rise to an excess negative charge on the electrode that is relieved by a flow of electrons through the external circuit to the positive (cathode) electrode. At the positive electrode, the lead of PbO2 is also converted to PbSO4 and, at the same time, water is formed. The reaction can be expressed as

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

- During charging, the reactions on the anode and cathode are reversed as shown in Figure 4.4(b) that can be expressed by

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

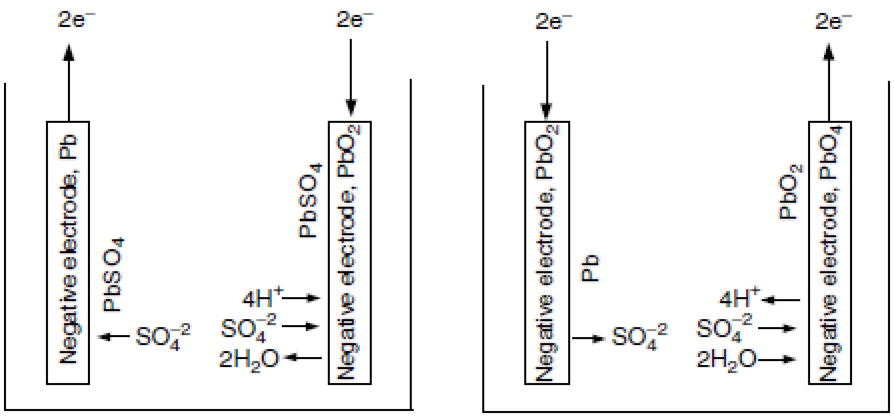
Cathode: $$PbSO_4 + 2H_2O \rightarrow PbO_2 + 4H^+ + SO_4^{2-} + 2e^-$$

ELECTROCHEMICAL BATTERIES

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

Overall: $$Pb + PbO_2 + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftharpoons}} 2PbSO_4 + 2H_2O.$$

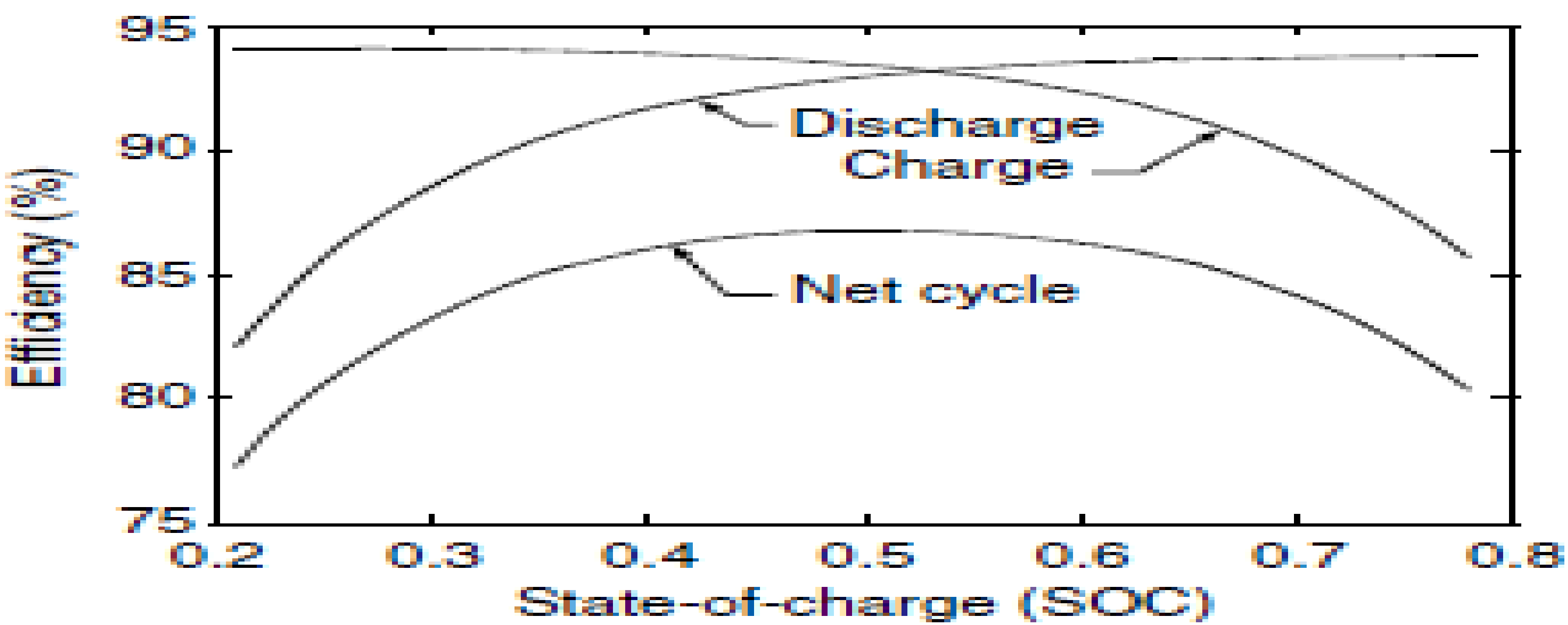
- Electrochemical processes during the discharge and charge of a lead-acid battery cell The lead-acid battery has a cell voltage of about 2.03 V at standard condition, which is affected by the concentration of the electrolyte.



(a) Discharging (b) Charging

BATTERY TECHNOLOGY

- The viable EV and HEV batteries consist of the lead-acid battery, nickel based batteries such as nickel/iron, nickel/cadmium, and nickel–metal hydride batteries, and lithium-based batteries such as lithium polymer and lithium-ion batteries.
- In the near term, it seems that lead-acid batteries will still be the major type due to its many advantages. However, in the middle and long term, it seems that cadmium- and lithium-based batteries will be major candidates for EVs and HEVs.
- **Typical battery charge and discharge efficiency:**



LEAD-ACID BATTERIES

- The lead-acid battery has been a successful commercial product for over a century and is still widely used as electrical energy storage in the automotive field and other applications.
- Its advantages are its low cost, mature technology, relative high-power capability, and good cycle. These advantages are attractive for its application in HEVs where high power is the first consideration. The materials involved (lead, lead oxide, sulfuric acid) are rather low in cost when compared to their more advanced counterparts.
- Lead-acid batteries also have several disadvantages. The energy density of lead-acid batteries is low, mostly because of the high molecular weight of lead.
- The temperature characteristics are poor.2 Below 10°C, its specific power and specific energy are greatly reduced. This aspect severely limits the application of lead-acid batteries for the traction of vehicles operating in cold climates.
- The presence of highly corrosive sulfuric acid is a potential safety hazard for vehicle occupants. Hydrogen released by the self-discharge reactions is another potential danger, since this gas is extremely flammable even intiny concentrations. Hydrogen emission is also a problem for hermetically sealed batteries.
- Indeed, in order to provide a good level of protection against acid spills, it is necessary to seal the battery, thus trapping the parasitic gases in the casing. As a result, pressure may build up in the battery, causing swelling and mechanical constraints on the casing and sealing.
- The lead in the electrodes is an environmental problem because of its toxicity. The emission of lead consecutive to the use of lead-acid batteries may occur during the fabrication of the batteries, in case of vehicle wreck (spill of electrolyte through cracks), or during their disposal at the end of battery life.

LEAD-ACID BATTERIES

- Different lead-acid batteries with improved performance are being developed for EVs and HEVs. Improvements of the sealed lead-acid batteries in specific energy over 40 Wh/kg, with the possibility of rapid charge, have been attained. One of these advanced sealed lead-acid batteries is Electro source's Horizon battery.
- It adopts the lead wire woven horizontal plate and hence offers the competitive advantages of high specific energy(43 Wh/kg), high specific power (285 W/kg), long cycle life (over 600 cycles for on-road EV application), rapid recharge capability (50% capacity in 8 min and 100% in less than 30 min), low cost (US$2000–3000 an EV), mechanical ruggedness (robust structure of horizontal plate), maintenance-free conditions(sealed battery technology), and environmental friendliness.
- Other advanced lead-acid battery technologies include bipolar designs and microtubular grid designs. Advanced lead-acid batteries have been developed to remedy these disadvantages.
- The specific energy has been increased through the reduction of inactive materials such as the casing, current collector, separators, etc. The lifetime has been increased by over 50% — at the expense of cost, however.

NICKEL-BASED BATTERIES

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

NICKEL/IRON SYSTEM:

- The nickel/iron system was commercialized during the early years of the20th century. Applications included fork-lift trucks, mine locomotives, shuttle vehicles, railway locomotives, and motorized hand-trucks.
- The system comprises a nickel hydroxy-oxide (NiOOH) positive electrode and a metallic iron negative electrode.
- The electrolyte is a concentrated solution of potassium hydroxide (typically 240 g/l) containing lithium hydroxide (50 g/l). The cell reaction is given in Table 10.1 and its nominal open-circuit
- voltage is 1.37 V. Nickel/iron batteries suffer from gassing, corrosion, and self-discharge problems. These problems have been partially or totally solved in prototypes that have yet to reach the market. These batteries are complex due to the need to maintain the water level and the safe disposal of the hydrogen and
- oxygen released during the discharge process. Nickel–iron batteries also suffer from low temperatures, although less than lead-acid batteries.
- Finally, the cost of nickel is significantly higher than that of lead. Their greatest advantages are high power density compared with lead-acid batteries, and a capability of withstanding 2000 deep discharges.

NICKEL/CADMIUM SYSTEM:

- The nickel/cadmium system uses the same positive electrodes and electrolyte as the nickel/iron system, in combination with metallic cadmium negative electrodes. The cell reaction is given in Table 10.1 and its nominal open-circuit voltage is 1.3 V.
- Historically, the development of the battery has coincided with that of nickel/iron and they have a similar performance.
- Nickel/cadmium technology has seen enormous technical improvement because of the advantages of high specific power (over 220 W/kg), long cycle life (up to 2000 cycles), a high tolerance of electric and mechanical abuse, a small voltage drop over a wide range of discharge currents, rapid charge capability (about 40 to 80% in 18 min), wide operating temperature(_40 to 85°C), low self-discharge rate (_0.5% per day), excellent long-term storage due to negligible corrosion, and availability in a variety of size designs

NICKEL-BASED BATTERIES

NICKEL/CADMIUM SYSTEM:

- However, the nickel/cadmium battery has some disadvantages, including high initial cost, relatively low cell voltage, and the carcinogenicity and environmental hazard of cadmium.
- Nickel/iron batteries suffer from gassing, corrosion, and self-discharge problems. These problems have been partially or totally solved in prototypes that have yet to reach the market.
- These batteries are complex due to the need to maintain the water level and the safe disposal of the hydrogen and oxygen released during the discharge process.
- Nickel–iron batteries also suffer from low temperatures, although less than lead-acid batteries. Finally, the cost of nickel is significantly higher than that of lead.
- Their greatest advantages are high power density compared with lead-acid batteries, and a capability of withstanding 2000 deep discharges

NICKEL-BASED BATTERIES

NICKEL–METAL HYDRIDE (NI–MH)BATTERY:

- The Nickel-metal hydride battery has been on the market since 1992. Its characteristics are similar to those of the nickel/cadmium battery.
- The principal difference between them is the use of hydrogen, absorbed in a metal hydride, for the active negative electrode material in place of cadmium. Because of its superior specific energy when compared to the Ni–Cd and its freedom fron$MH + NiOOH \leftrightarrow M + Ni(OH)_2$. city, the Ni–MH battery is superseding the Ni–Cd battery.
- The overall reaction in a Ni–MH battery is
- When the battery is discharged, the metal hydride in the negative electrode is oxidized to form metal alloy, and nickel oxyhydroxide in the positive electrode is reduced to nickel hydroxide. During charging, the reverse reaction occurs.
- At present, Ni–MH battery technology has a nominal voltage of 1.2 V and attains a specific energy of 65 Wh/kg and a specific power of 200 W/kg.

ULTRA OR SUPERCAPACITOR

- Because of the frequent stop/go operation of EVs and HEVs, the discharging and charging profile of the energy storage is highly varied. The average power required from the energy storage is much lower than the peak power of relatively short duration required for acceleration and hill climbing.
- In fact, the energy involved in the acceleration and deceleration transients is roughly two thirds of the total amount of energy over the entire vehicle mission in urban driving .
- In HEV design, the peak power capacity of the energy storage is more important than its energy capacity, and usually constrains its size reduction.
- Based on present battery technology, battery design has to carry out the trade-off among the specific energy and specific power and cycle life.
- The difficulty in simultaneously obtaining high values of specific energy, specific power, and cycle life has led to some suggestions that the energy storage system of EV and HEV should be a hybridization of an energy source and a power source.
- The energy source, mainly batteries and fuel cells, has high specific energy whereas the power source has high specific power.
- The power sources can be recharged from the energy source during less demanding driving or regenerative braking. The power source that has received wide attention is the ultracapacitor

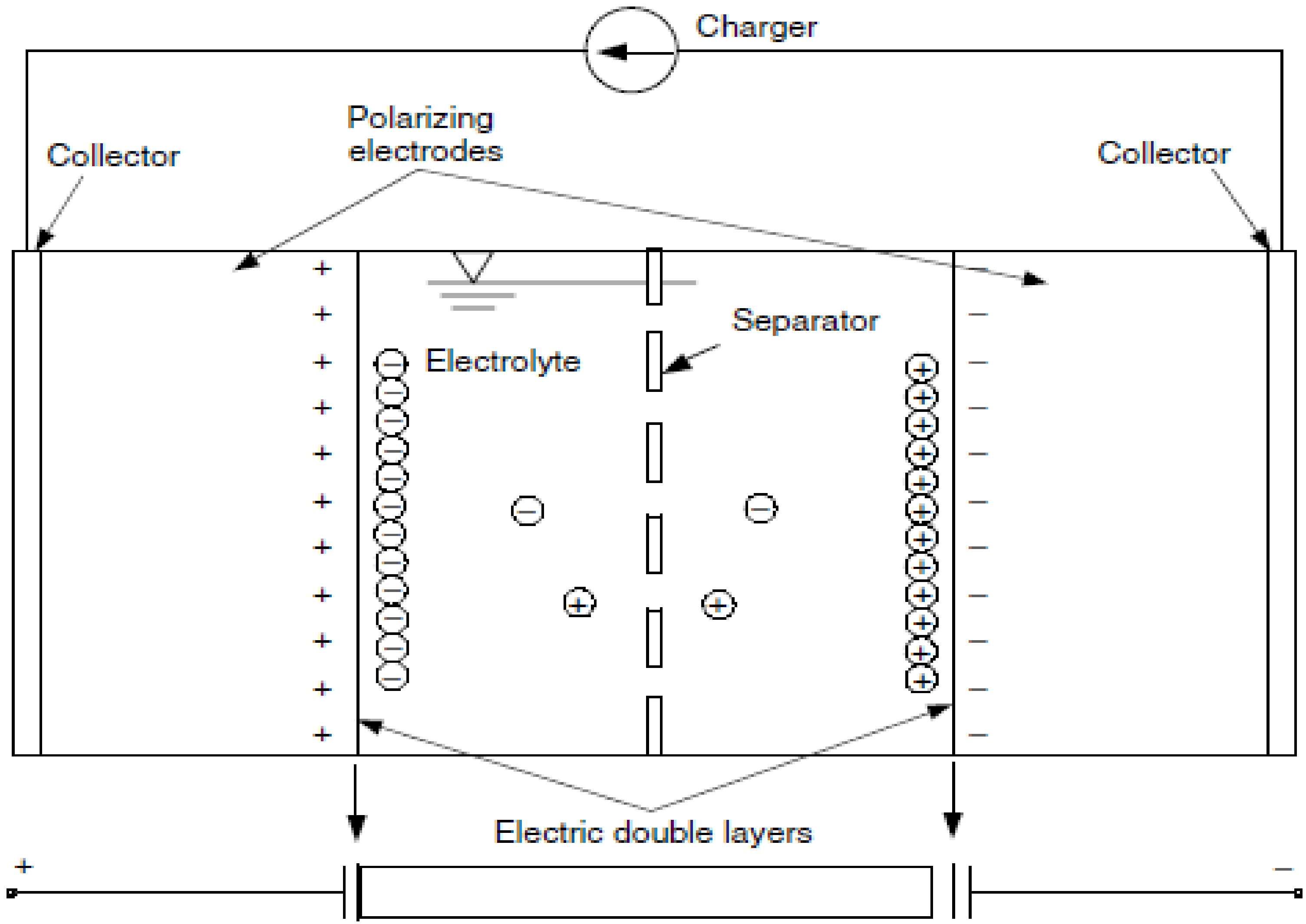
ULTRA OR SUPERCAPACITOR

FEATURES OF ULTRACAPACITORS:

- The ultracapacitor is characterized by much higher specific power, but much lower specific energy compared to the chemical batteries. Its specific energy is in the range of a few watt-hours per kilogram.
- However, its specific power can reach up to 3 kW/kg, much higher than any type of battery.
- Due to their low specific energy density and the dependence of voltage on the SOC, it is difficult to use ultracapacitors alone as an energy storage for EVs and HEVs. Nevertheless, there are a number of advantages that can result from using the ultracapacitor as an auxiliary power source.
- One promising application is the so-called battery and ultracapacitor hybrid energy storage system for EVs and HEVs.
- Specific energy and specific power requirements can be decoupled, thus affording an opportunity to design a battery that is optimized for the specific energy and cycle life with little attention being paid to the specific power.
- Due to the load levelling effect of the ultracapacitor, the high-current discharging from the battery and the high-current charging to the battery by regenerative braking is minimized so that the available energy, endurance, and life of the battery can be significantly increased.

ULTRA OR SUPERCAPACITOR

BASIC PRINCIPLES OF ULTRACAPACITORS:



ULTRA OR SUPERCAPACITOR

- **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 .
- 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, *Ecap*, is expressed as

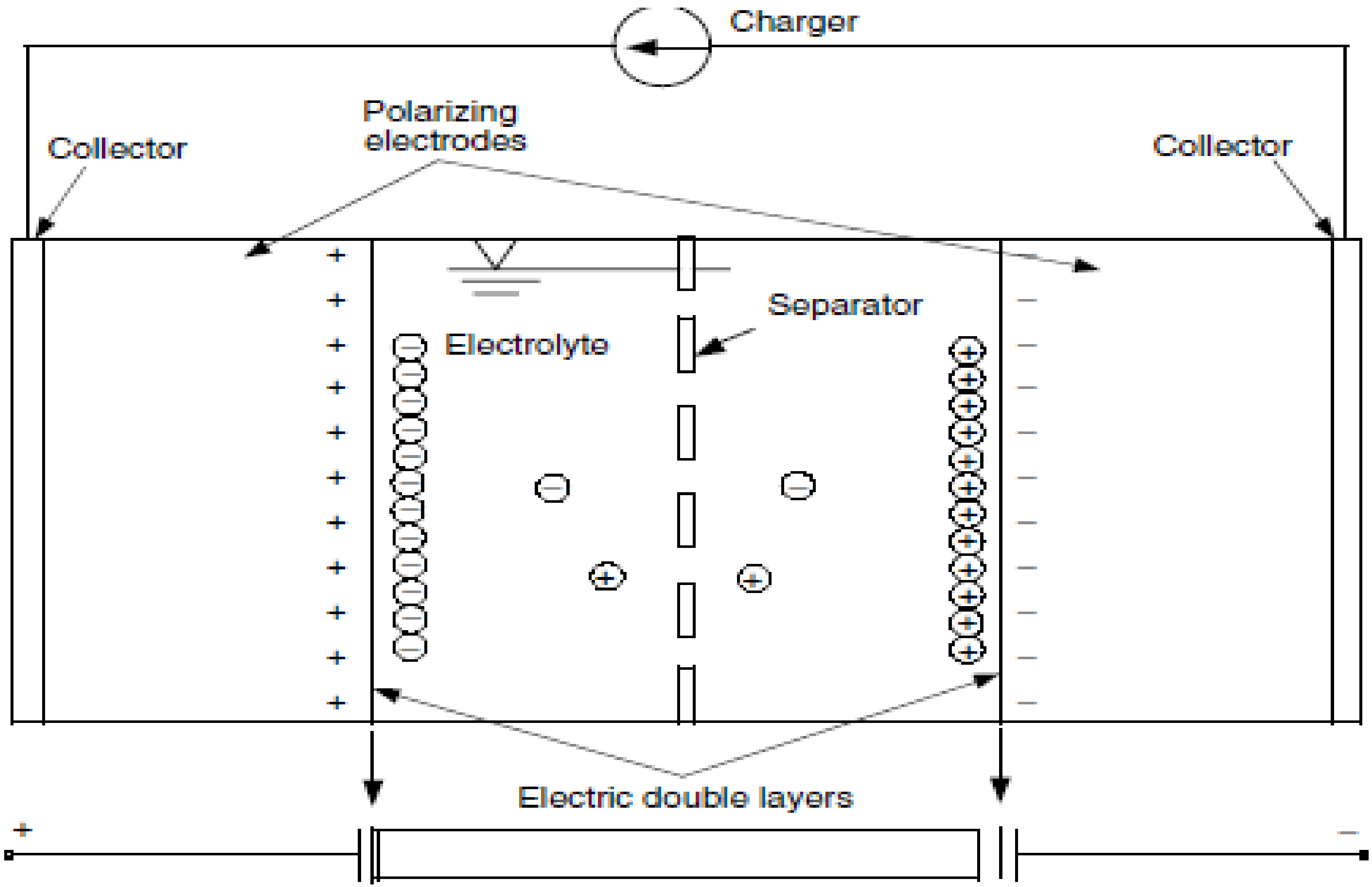
$$E_{cap} = \frac{1}{2} C V^2,$$

- 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.

ULTRA OR SUPERCAPACITOR

- There is great merit in using an electric double layer in place of plastic or aluminium oxide films in a capacitor, since the double layer is very thin — as thin as one molecule with no pin holes — and the capacity per area is quite large, at 2.5 to 5 μF/cm2.Even if a few μF/cm2 are obtainable, the energy density of capacitors is not large when using aluminium foil.
- For increasing capacitance, electrodes are made from specific materials that have a very large area, such as activated carbons, which are famous for their surface areas of 1,000 to 3,000 m2/g. To those surfaces, ions are adsorbed and result in 50 F/g (1,000 m2/g_5F/cm2_10,000 cm2/m2_50 F/g).
- Assuming that the same weight of electrolyte is added, 25 F/g is quite a large capacity density. Nevertheless, the energy density of these capacitors is far smaller than secondary batteries.
- the typical specific energy of ultracapacitors at present is about 2 Wh/kg, only1/20 of 40 Wh/kg, which is the available value of typical lead-acid batteries.

ULTRA OR SUPERCAPACITOR



ULTRA OR SUPERCAPACITOR

Performance of Ultracapacitors:

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

$$V_t = V_C - iR_S.$$

- The electric potential of a capacitor can be expressed by

$$\frac{dV_C}{dt} = -\left(\frac{i+i_L}{C}\right),$$

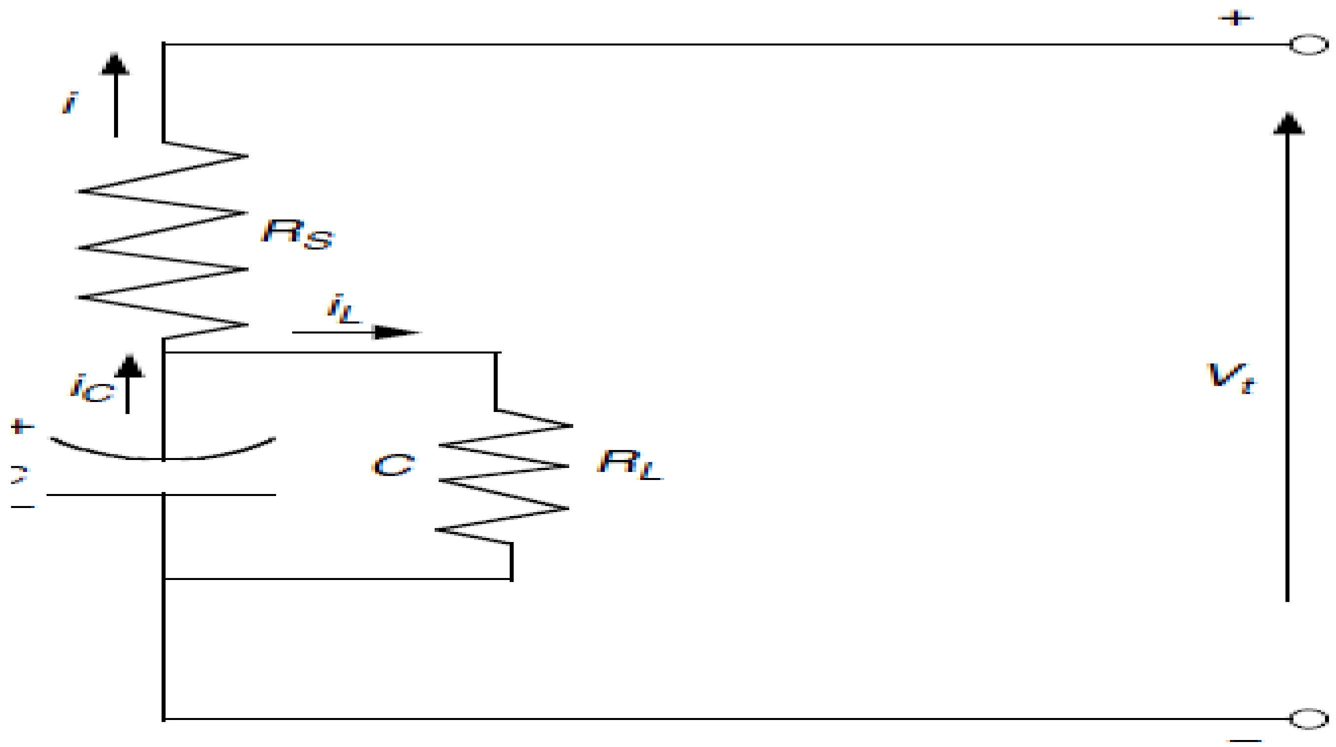
- where *C* is the capacitance of the ultracapacitor. On the other hand, the leakage current *iL* can be expressed as

$$i_L = \frac{V_c}{R_L}.$$

$$V_C = \left[V_{C0}\int_0^t \frac{i}{C} e^{t/CR_L}\, dt\right] e^{t/CR_L},$$

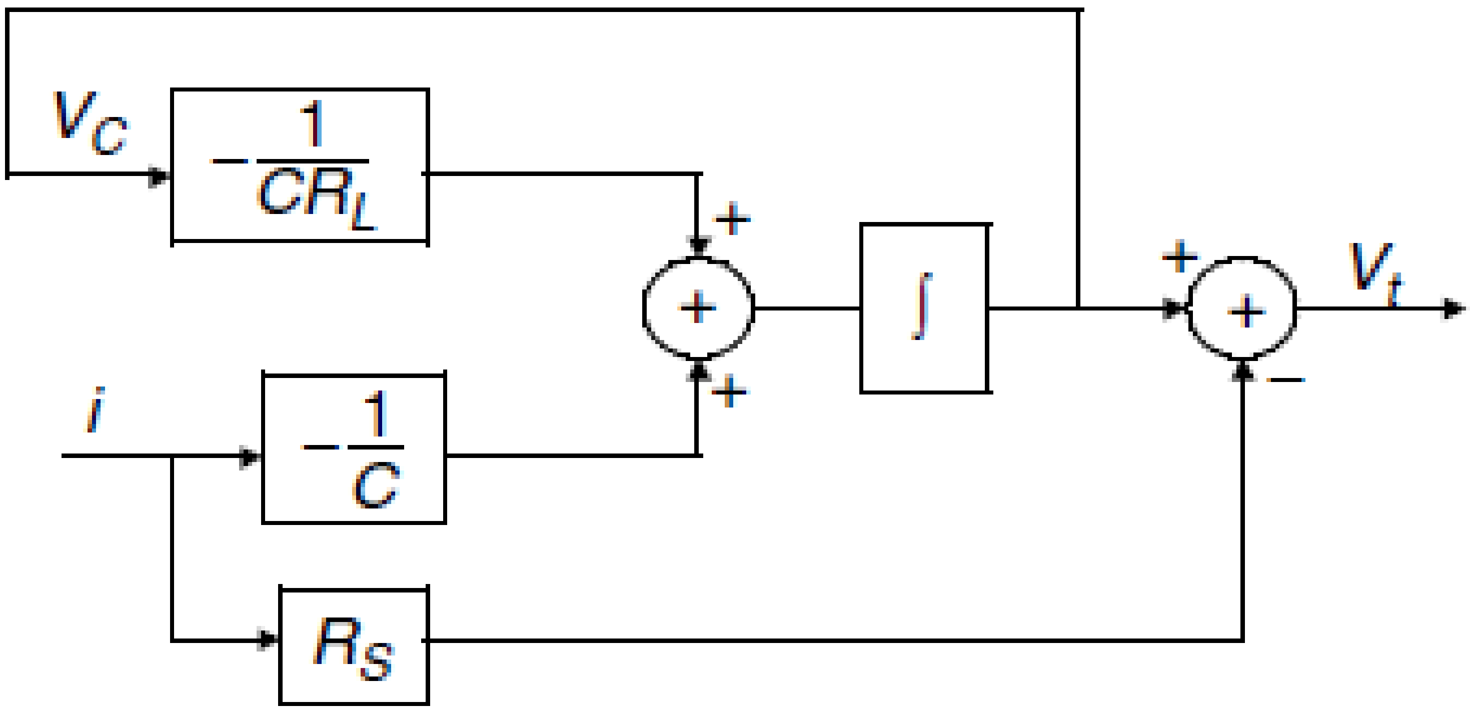
Performance of Ultracapacitors:

- Ultracapacitor equivalent circuit:



Performance of Ultracapacitors:

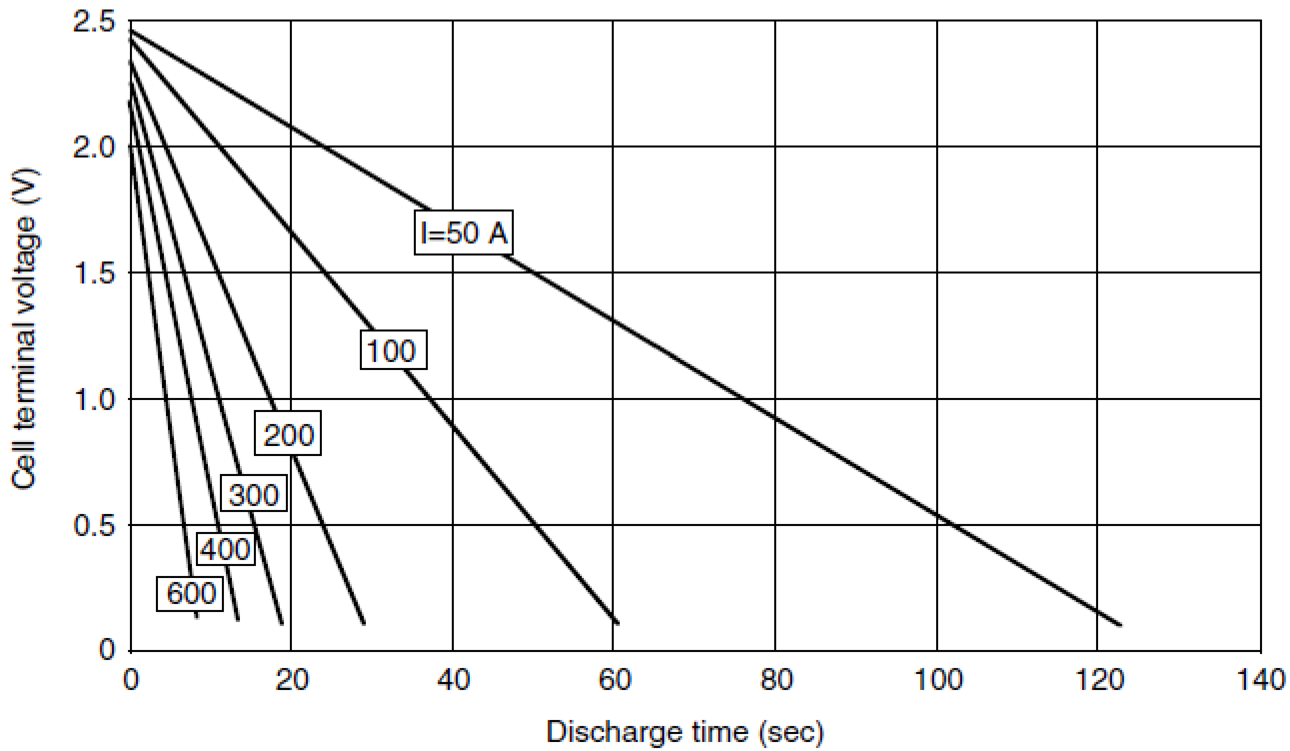
- Block diagram of the ultracapacitor model:



ULTRA OR SUPERCAPACITOR

Performance of Ultracapacitors:

- Discharge characteristics of the 2600 F Maxwell Technologies ultracapacitor:



ULTRAHIGH-SPEED FLYWHEELS

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

ULTRAHIGH-SPEED FLYWHEELS

POWER CAPACITY OF FLYWHEEL SYSTEMS:

- The power that a flywheel delivers or obtains can be obtained by differentiating equation (1) with respect to time, that is,

$$P_f = \frac{dE_f}{dt} = J_f \omega_f \frac{d\omega_f}{dt} = \omega_f T_f,$$

- where *Tf* is the torque acting on the flywheel by the electric machine. When the flywheel discharges its energy, the electric machine acts as a generator and converts the mechanical energy of the flywheel into electric energy.
- On the other hand, when the flywheel is charged, the electric machine acts as a motor and converts electric energy into mechanical energy stored in the flywheel.
- An electric machine usually has the characteristics as shown in Figure 4.19, which has two distinct operating regions — constant torque and constant power region.
- In the constant torque region, the voltage of the electric machine is proportional to its angular velocity, and the magnetic flux in the air gap is constant.
- However, in the constant power region, the voltage is constant and the magnetic field is weakened with increasing machine angular velocity.

ULTRAHIGH-SPEED FLYWHEELS

POWER CAPACITY OF FLYWHEEL SYSTEMS:

- In charge of the flywheel, that is, accelerating the flywheel from a low speed, ω0, to a high speed, maximum speed, *ωmax*, for example, the torque delivered from the electric machine is

$$T_m = J_f \frac{d\omega_f}{dt},$$

- where it is supposed that the electric machine is directly connected to the flywheel. The time, *t*, needed can be expressed as

$$t = \int_{\omega_0}^{\omega_{max}} \frac{J_f}{T_m} d\omega = \int_{\omega_0}^{\omega_b} \frac{J_f}{p_m/\omega_b} \omega + \int_{\omega_b}^{\omega_{max}} \frac{J_f}{p_m/\omega} d\omega .$$

- the maximum power of the electric machine can be obtained from as

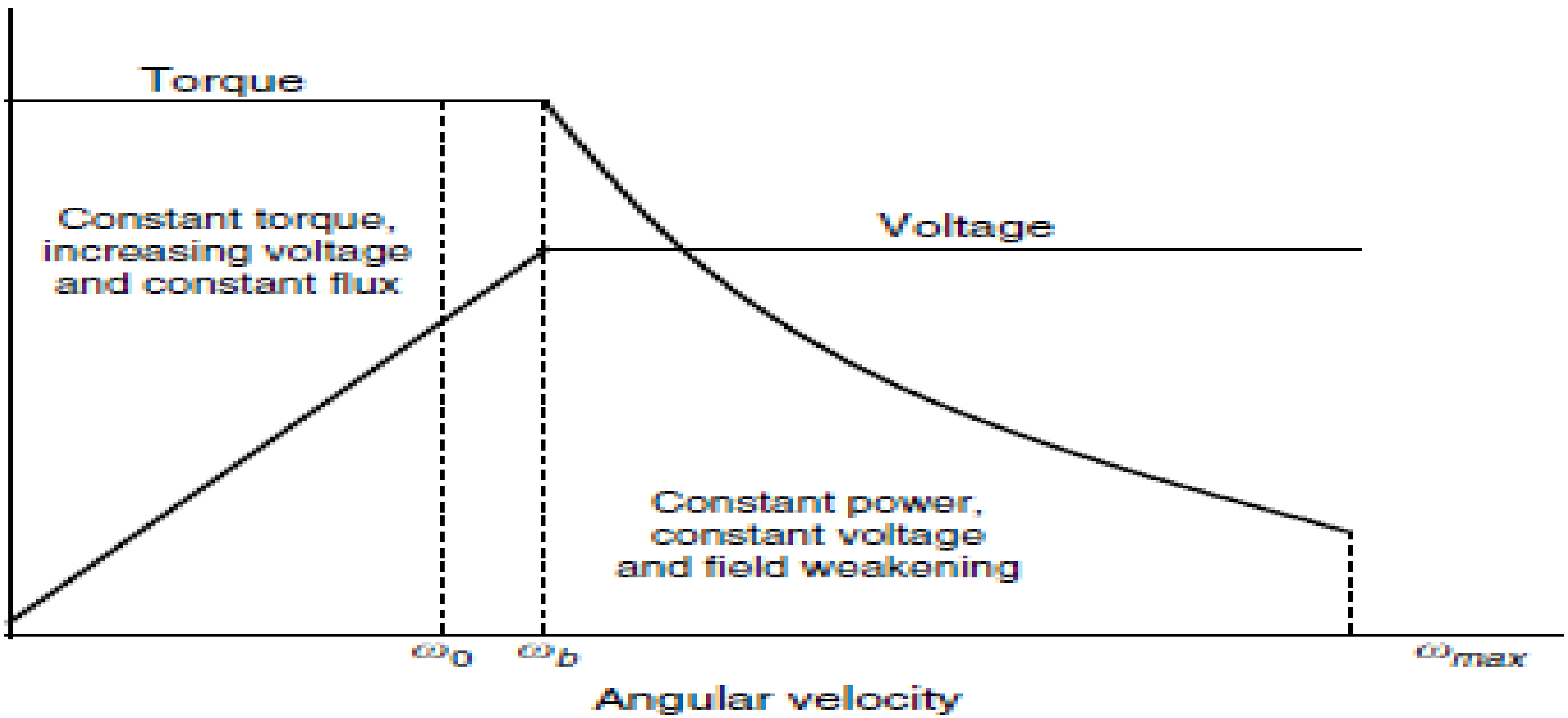
$$P_m = \frac{J_f}{2_t} \left(\omega_b^2 - 2\omega_0 \omega_b + \omega_{max}^2 \right).$$

- the power of the electric machine can be minimized by the design of its corner speed or base speed, *ωb*, equal to the bottom speed of the flywheel, ω0.
- This conclusion implies that the effective operating speed range of the flywheel should coincide with the constant speed region of the electric machine. The power of the electric machine can be minimized as

$$P_m = \frac{J_f}{2_t} \left(\omega_0^2 + \omega_{max}^2 \right).$$

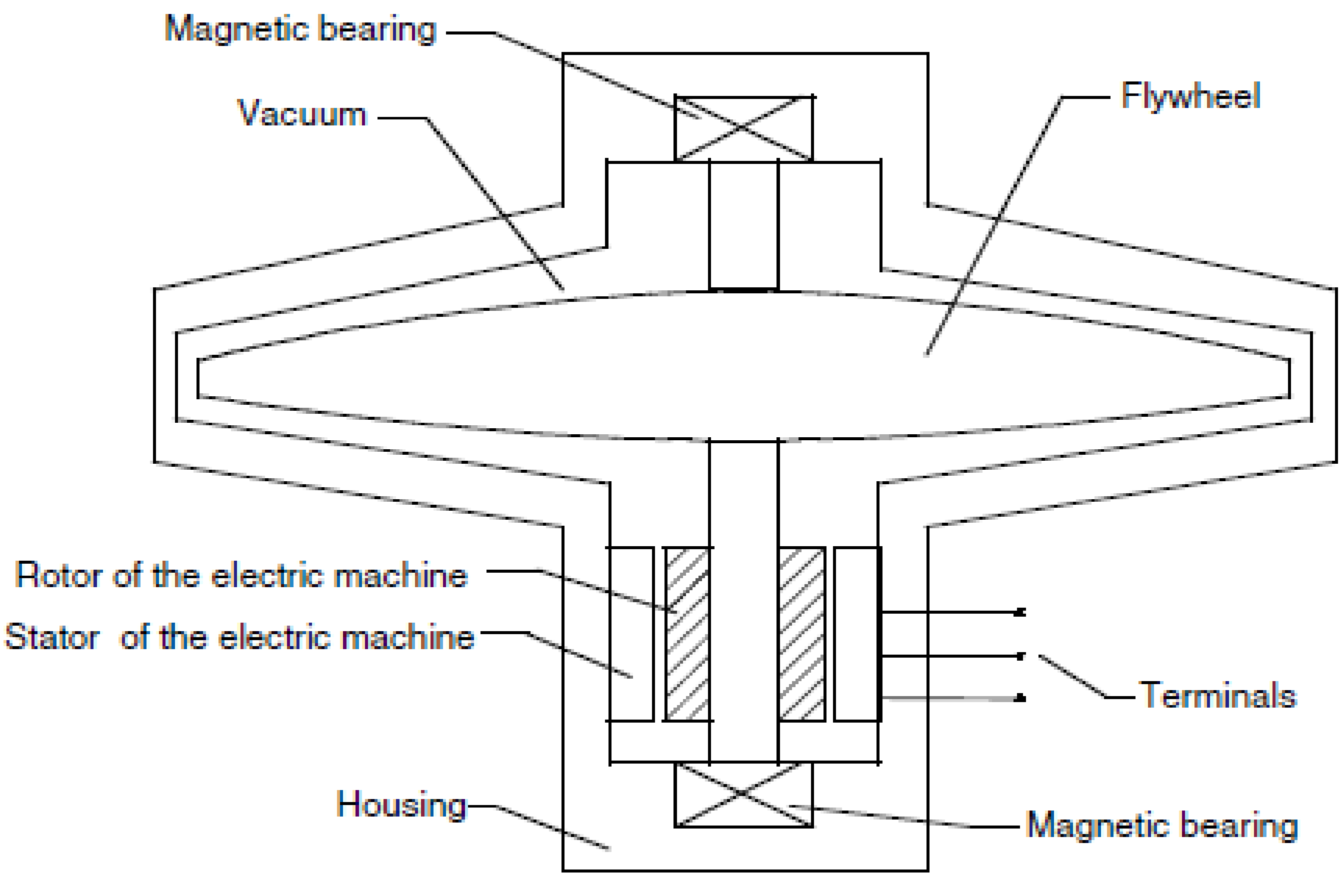
POWER CAPACITY OF FLYWHEEL SYSTEMS:

- Another advantage achieved by coinciding the operating speed range of the flywheel with the constant power speed range is that the voltage of the electric machine is always constant , therefore significantly simplifying the power management system, such as DC/DC converters and their controls.
- Typical torque and voltage profile vs. rotational speed:



ULTRAHIGH-SPEED FLYWHEELS

- **FLYWHEEL TECHNOLOGIES:**
- Basic structure of a typical flywheel system:



FLYWHEEL TECHNOLOGIES:

- Although higher rotational speed can significantly increase the stored energy , there is a limit to which the tensile strength σ of the material constituting the flywheel cannot withstand the stress resulting from the centrifugal force.
- The maximum stress acting on the flywheel depends on its geometry, specific density ρ, and rotational speed.
- The maximum benefit can be obtained by adopting flywheel materials that have a maximum ratio of σ/ρ. Notice that if the speed of the flywheel is limited by the material strength, the theoretical specific energy is proportional to the ratio of σ/ρ.
- A constant-stress principle maybe employed for the design of ultrahigh speed flywheels. To achieve the maximum energy storage, every element in the rotor should be stressed equally to its maximum limit.
- Due to the extremely high rotating speed and in order to reduce the aerodynamic loss and frictional loss, the housing inside the flywheel in spinning is always highly vacuumed, and noncontact, magnetic bearings are employed.

ULTRAHIGH-SPEED FLYWHEELS

FLYWHEEL TECHNOLOGIES:

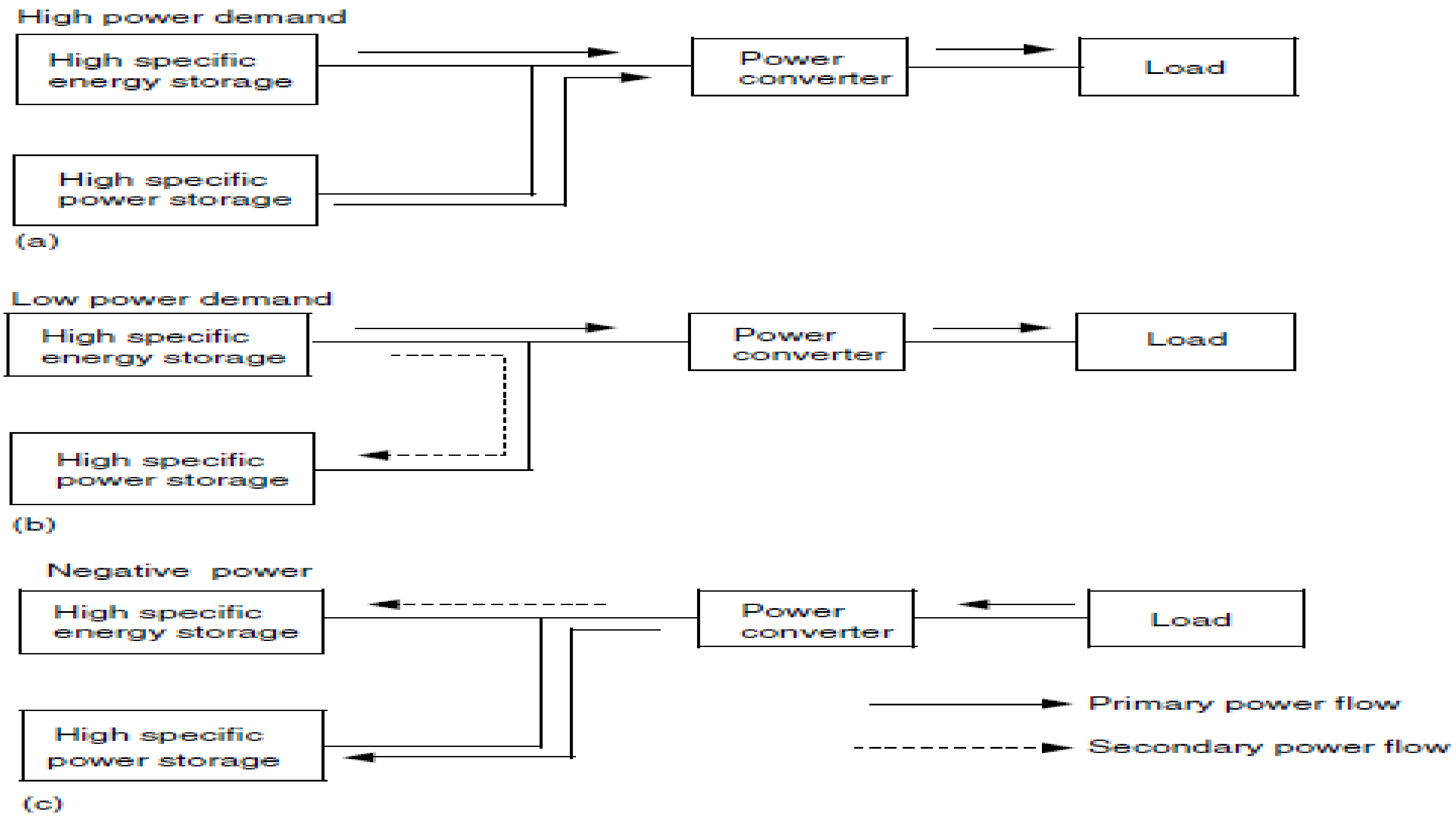
- The electric machine is one of the most important components in the flywheel system, since it has critical impact on the performance of the system.
- At present, permanent magnet (PM) brushless DC motors are usually accepted in the flywheel system.
- Apart from possessing high power density and high efficiency, the PM brushless DC motor has a unique advantage that no heat is generated inside the PM rotor, which is particularly essential for the rotor to work in a vacuum environment to minimize the windage loss A switched reluctance machine (SRM) is also a very promising candidate for the application in a flywheel system.
- SRM has a very simple structure and can operate efficiently at very high speed. In addition, SRM presents a large extended constant power speed region, which allows more energy in the flywheel that can be delivered. In this extended speed region, only the machine excitation flux is varied, and is easily realized.

HYBRIDIZATION OF ENERGY STORAGES

- The hybridization of energy storage is to combine two or more energy storages together so that the advantages of each one can be brought out and the disadvantages can be compensated by others.
- For instance, the hybridization of a chemical battery with an ultracapacitor can overcome such problems as low specific power of electrochemical batteries and low specific energy of ultracapacitors, therefore achieving high specific energy and high specific power Basically, the hybridized energy storage consists of two basic energy storages:
- one with high specific energy and the other with high specific power. The basic operation of this system is illustrated .
- 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 21 (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 21 (b).

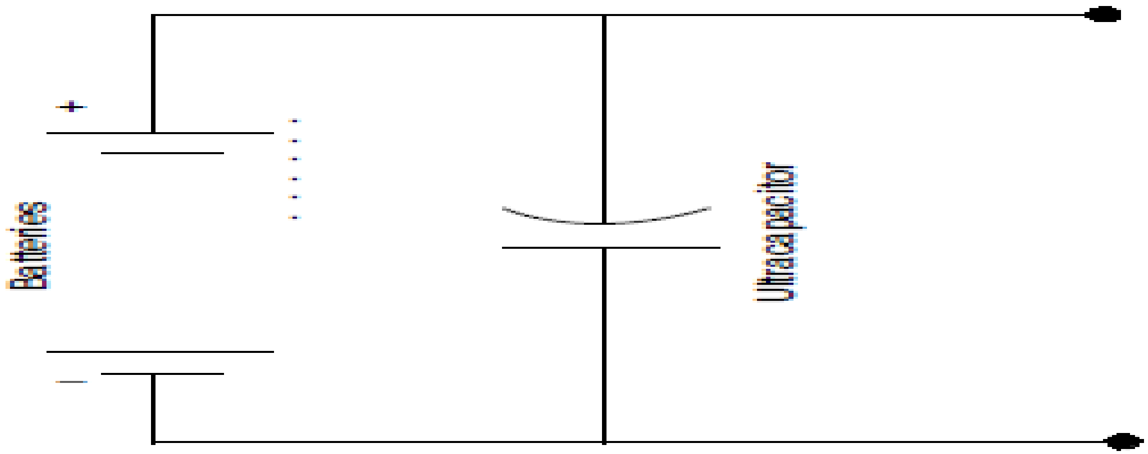
HYBRIDIZATION OF ENERGY STORAGES

- Concept of a hybrid energy storage operation:



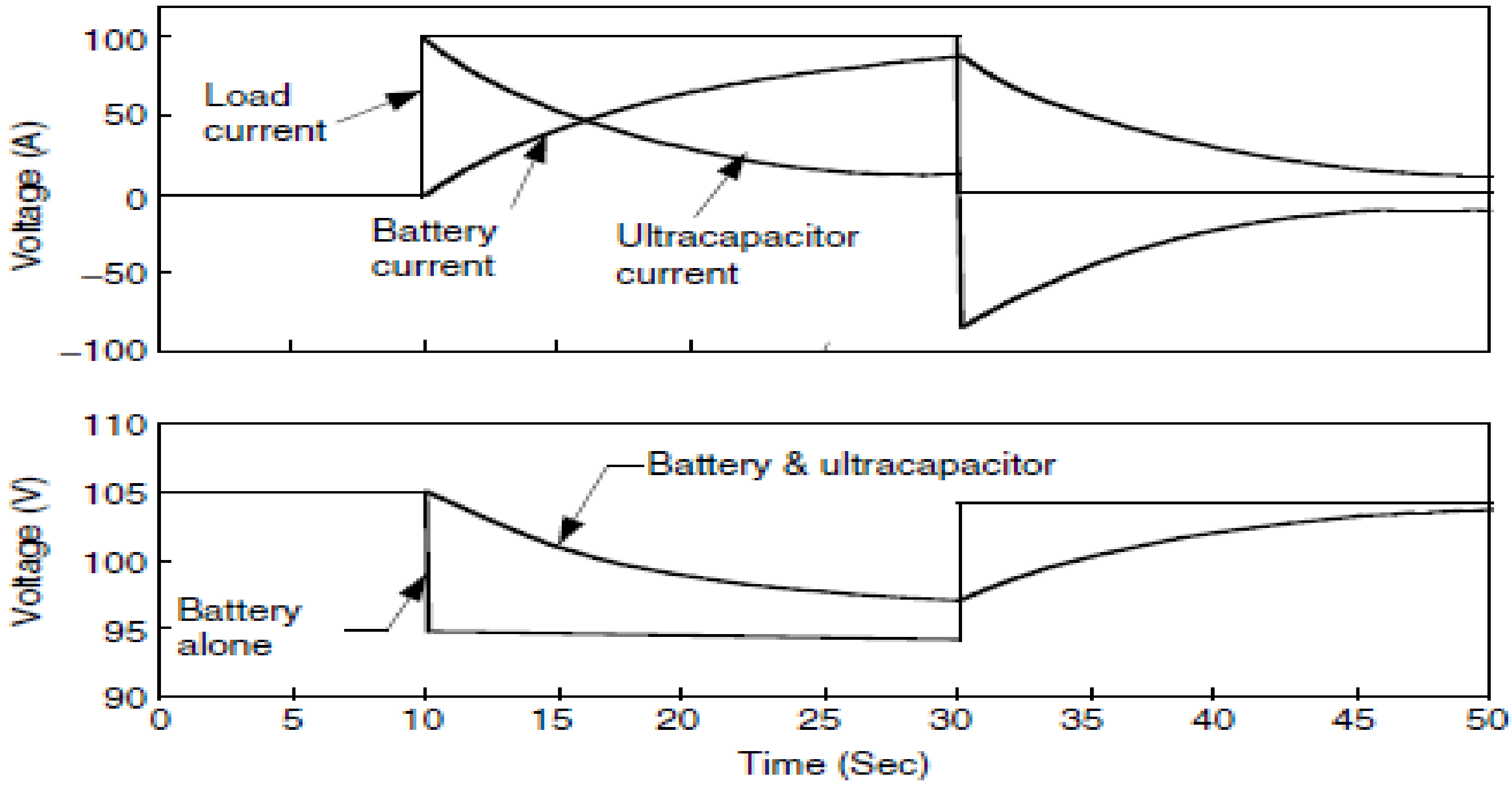
HYBRIDIZATION OF ENERGY STORAGES

- In regenerative braking operations, the peak power will be absorbed by the high specific power storage, and only a limited part is absorbed by the high specific energy storage.
- In this way, the whole system would be much smaller in weight and size than if any one of them alone was the energy storage.
- Based on the available technologies of various energy storages, there are several viable hybridization schemes for EVs and HEVs, typically, battery and battery hybrids, and battery and ultracapacitor hybrids. The latter is more natural since the ultracapacitor can offer much higher power than batteries, and it collaborates with various batteries to form the battery and ultracapacitor hybrids.
- During hybridization, the simplest way is to connect the ultracapacitors to the batteries directly and in parallel, as shown in Figure 4.22



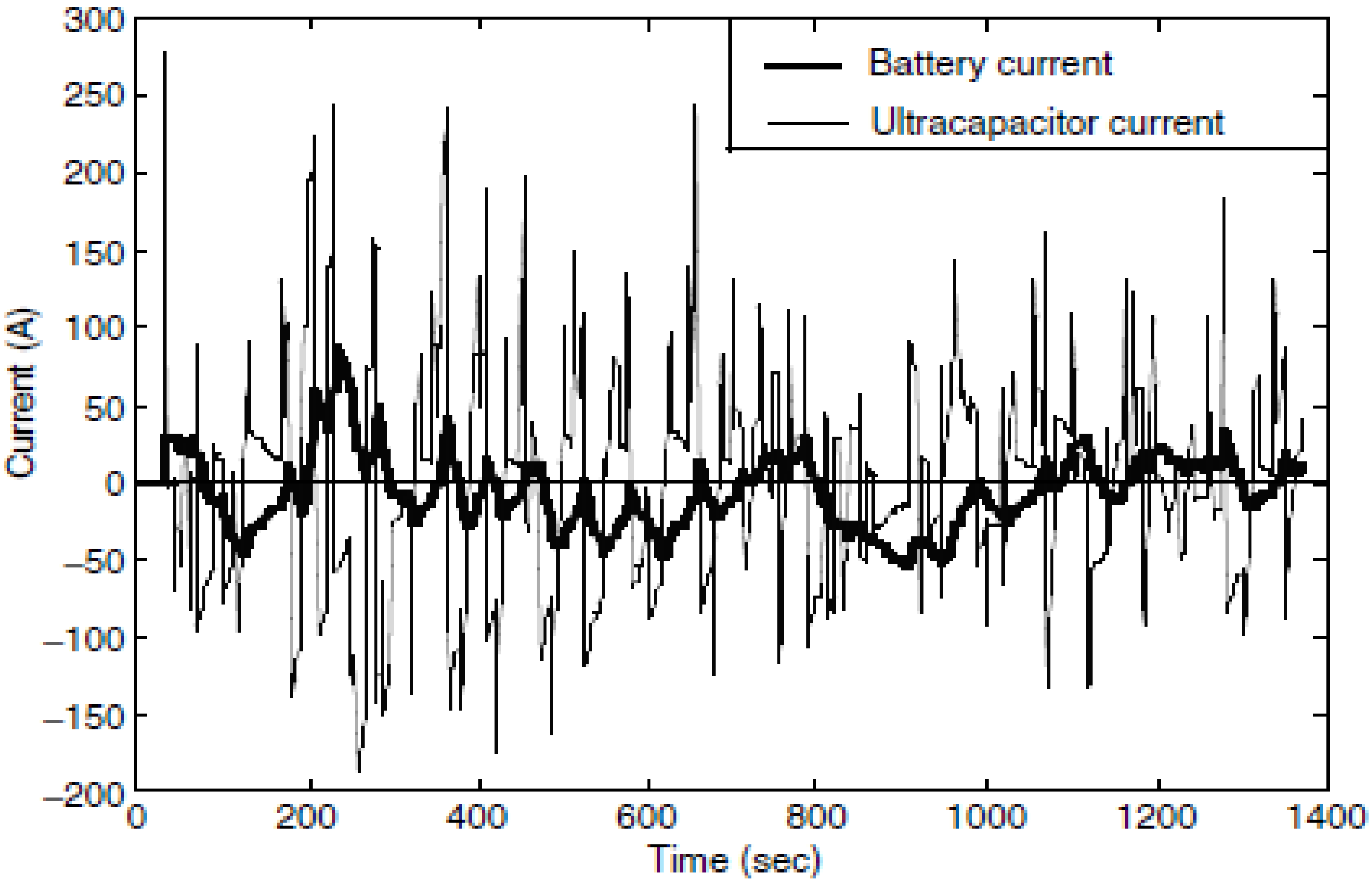
HYBRIDIZATION OF ENERGY STORAGES

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



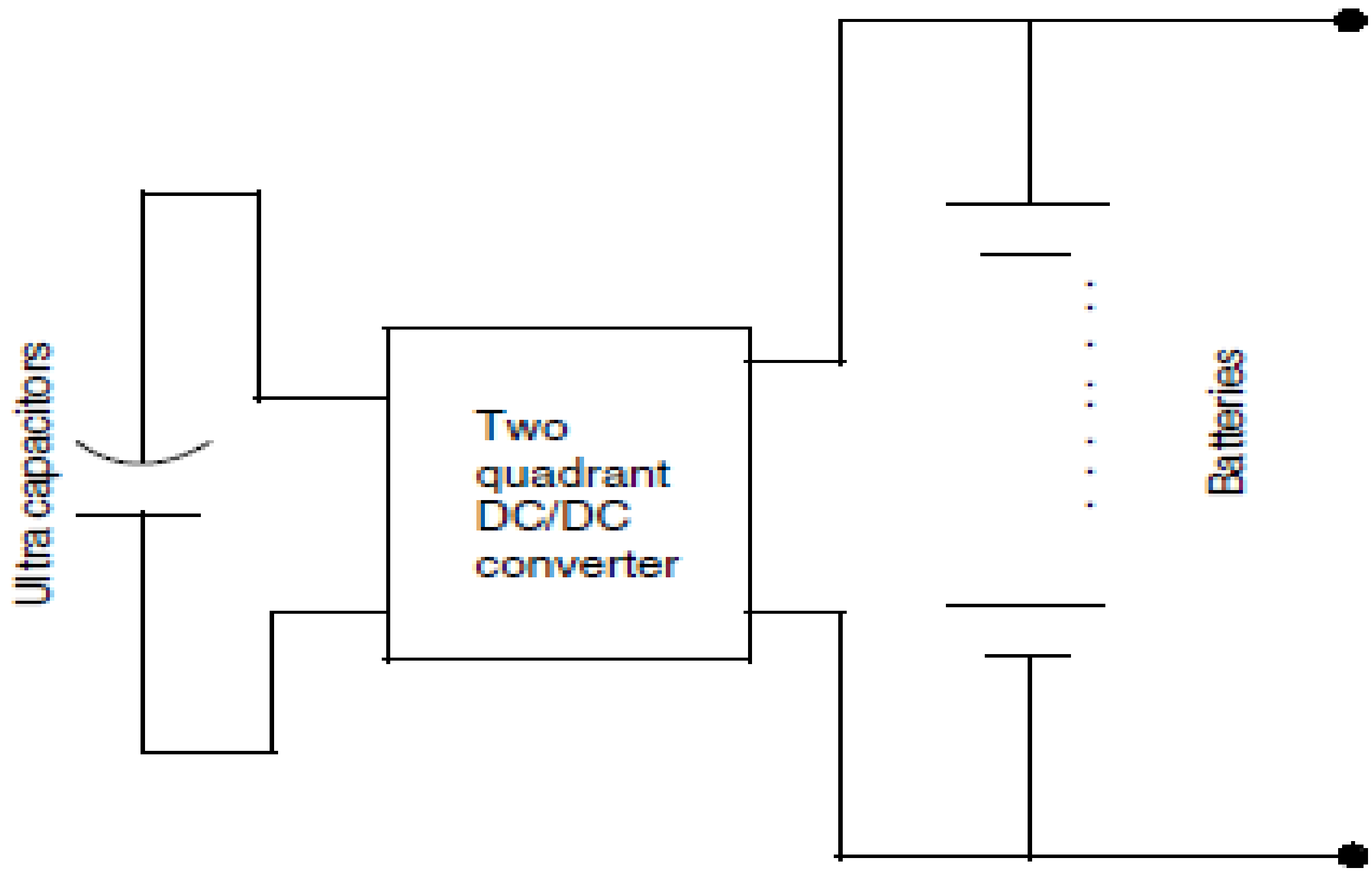
HYBRIDIZATION OF ENERGY STORAGES

- Battery and ultracapacitor currents during operation of HEV in an FTP 75 urban drive cycle



HYBRIDIZATION OF ENERGY STORAGES

- Actively controlled hybrid battery/ultracapacitor energy storage:



UNIT-V
ENERGY MANAGEMENT STRATEGIES

HYBRID ECU

- The hybrid ECU is the heart of the control architecture of any HEV and it is also known energy management strategy (EMS).
- **CLASSIFICATION OF HYBRID ECU:**

The EMS can be classified into following broad categories:

- Rule based
- Optimization based

The *Rule Based* strategies consist of following subcategories:

i. Fuzzy based: The fuzzy based control strategies are of three types

- Predictive,
- Adaptive
- Conventional

Deterministic Control: The deterministic controllers are subdivided into

- State Machine
- Power follower
- Thermostat Control

Optimization based strategies

i. Global Optimization: The global optimization methods are:

- Linear programming methods
- Dynamic Programming
- Stochastic Dynamic Programming
- Genetic Algorithms

ii. Real time Optimization: The real time optimization techniques are of following types:

- EFC minimization
- Robust control
- Model predictive

Optimization based strategies

- In **Figure 1** the classification tree of the various control techniques is shown. In the subsequent sections the Rule based control strategies will be discussed in detail.

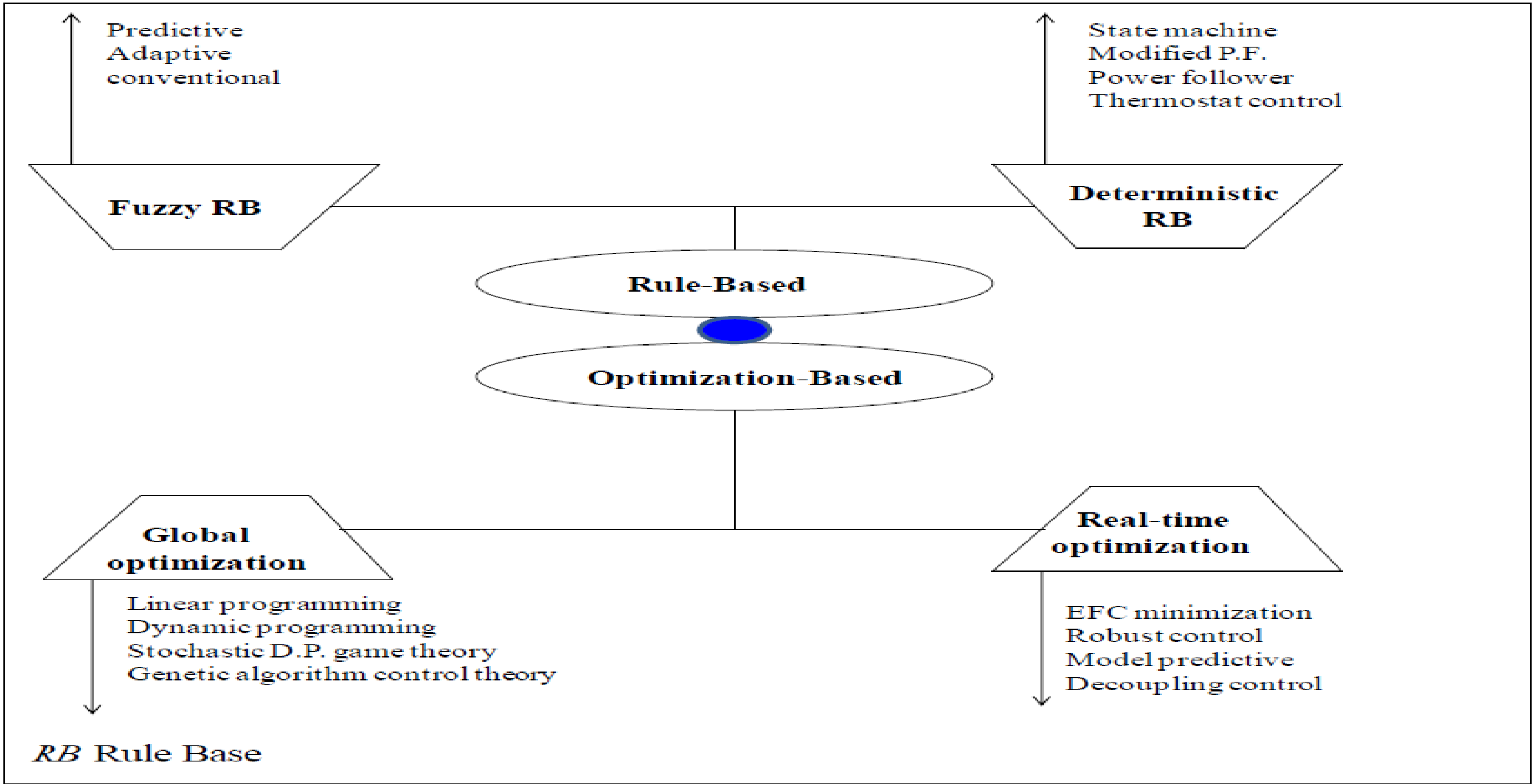


Figure 1: Classification of control strategies [1]

RULE BASED CONTROL METHODS

BASIC PRINCIPLES OF RULE BASED CONTROL METHODS:

Rule based control strategies can cope with the various operating modes of HEV. The rule-based strategies are developed using engineering insight and intuition, analysis of the ICE efficiency charts shown in **Figure 2** and the analysis of electrical component efficiency charts.

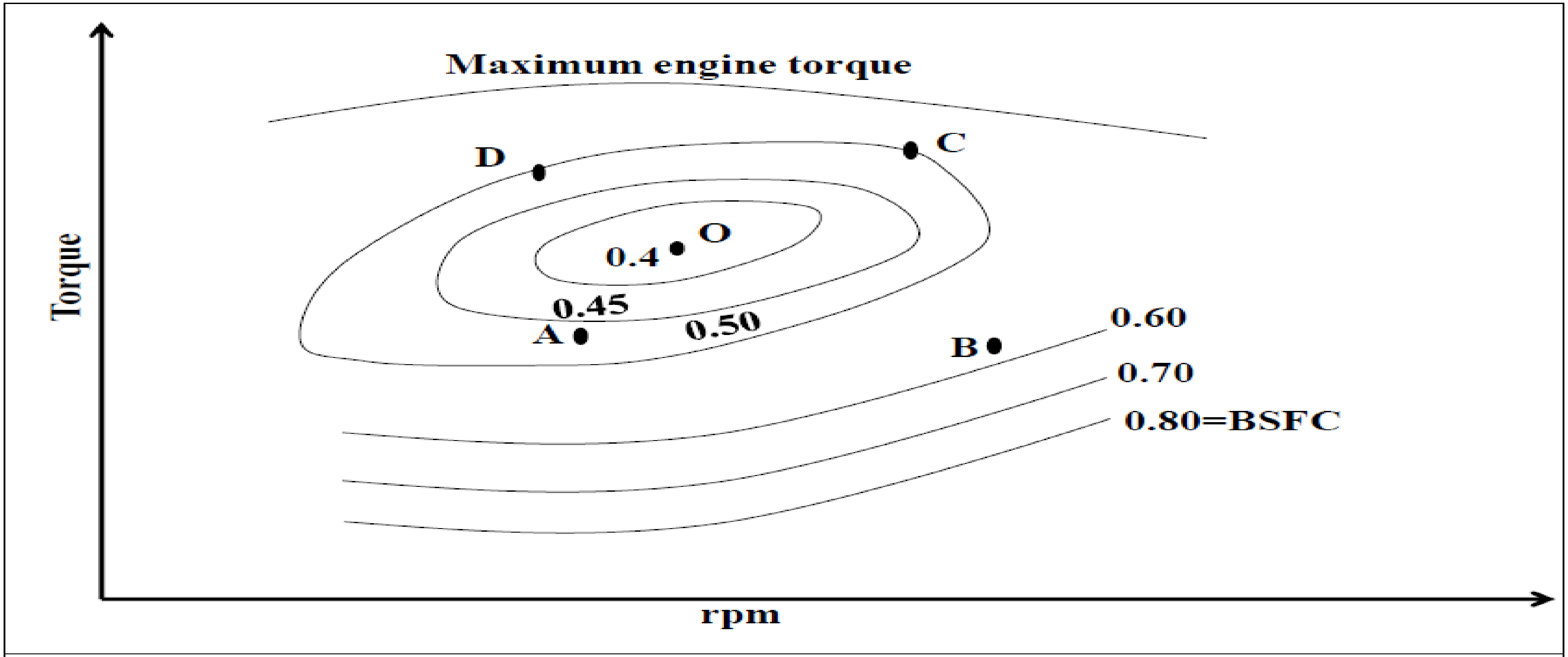


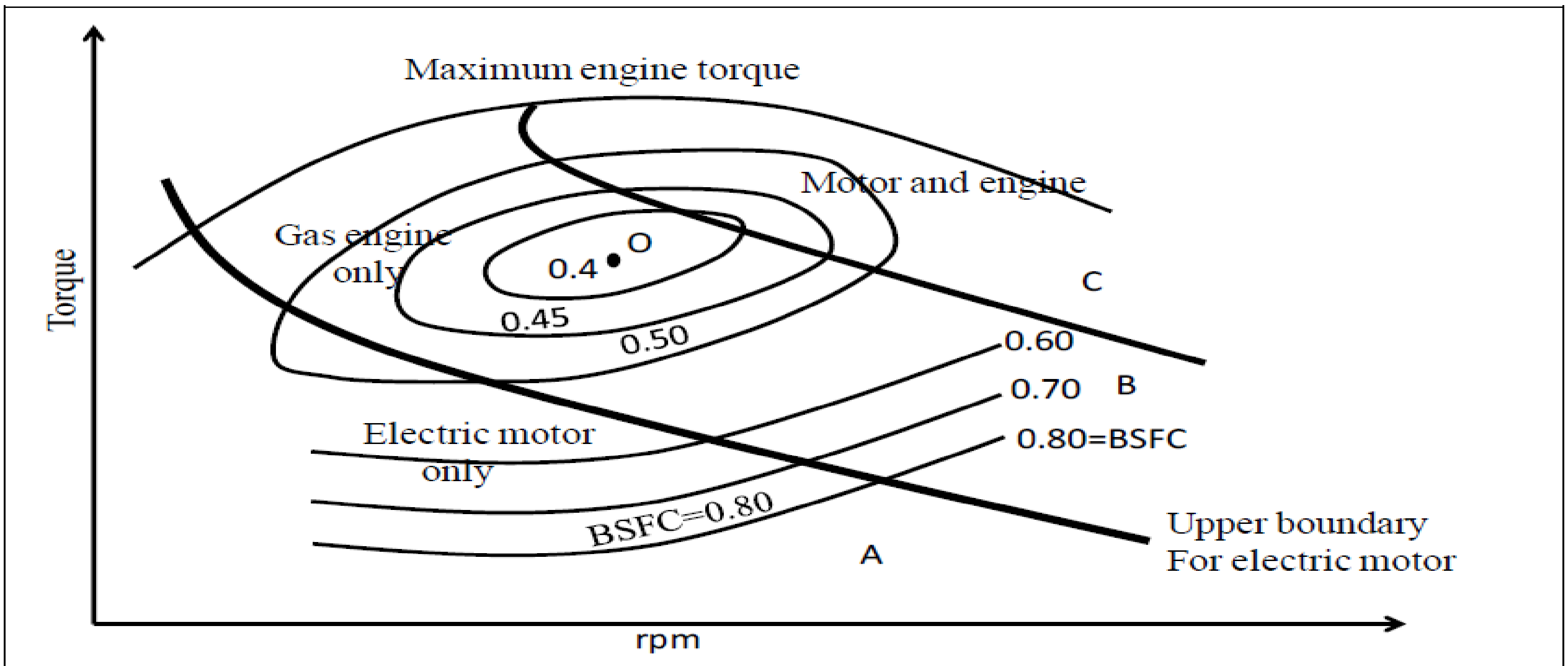
Figure 2: Efficiency map of ICE [1]

RULE BASED CONTROL METHODS

BASIC PRINCIPLES OF RULE BASED CONTROL METHODS:

An example of developing rule-based strategy can be explained using the ICE efficiency map shown in **Figure 3**. The lines, which are drawn using engineering insight and intuition, divide the map into three regions: **A**, **B**, and **C**. The rules for operation of ICE in these three regions are:

- In the region **A** only, EM is used because in this region the fuel efficiency of the ICE is poor.
- In region **B** only ICE is used since this the region of high fuel efficiency.
- In region **C** both ICE and EM are used.



DETERMINISTIC RULE BASED STRATEGIES

Heuristics based on analysis of power flow in HEV drivetrain, ICE efficiency map and human experiences are utilized to design deterministic rules. These rules are generally implemented using lookup tables to split requested power between the ICE and EM. The most commonly used strategies are:

- Thermostat (on/off) control
- Power follower control
- Modified power follower
- State Machine based controller

In the following sections the controllers marked in bold are explained. Power follower control In this strategy the ICE is the primary source of power and the EM is used to provide additional power when needed by the vehicle. Care is always taken to maintain the SOC of batteries within safe limits. The rule base that is generally used is:

- Below a certain minimum vehicle speed, only the EM is used.
- If the demanded power is greater than the maximum power that the ICE can produce at its operating speed, the EM is used to produce excess power.
- The EM charges the batteries by regenerative braking.
- The ICE shuts off when the power demand falls below a limit at the operating speed. This is done to prevent inefficient operation of ICE.
- This is a very simple and effective strategy but the major disadvantage is that the efficiency of the entire drivetrain is not optimized

MODIFIED POWER FOLLOWER

- In order to improve the power follower controller a cost function is introduced. The role of this cost function is to strike a balance between fuel consumption and emissions at all operating points of HEV. The rule base for the proposed strategy is as follows:
- Define the range of operating points: The range of operating points (distribution of ICE and EM torques) is represented by the range of acceptable motor torques for the current torque request. The relation between the ICE, EM and requested torque is given by

$$T_{ice} = T_{request} - KT_{em}$$

where

$K =$ motor to ICE gear ratio

The greatest possible positive motor torque defines one extreme of the operating point range: This value is the minimum of three values:

- The driver’s torque request
- The maximum rated positive torque of the motor at the current speed
- Maximum available positive torque from the EM, according to the limits imposed by the capability of the batteries

MODIFIED POWER FOLLOWER

- The greatest possible negative EM torque defines the other extreme of the operating point range. This value is the maximum of:
- The difference between the driver's torque request and the maximum positive torque available from the ICE
- The maximum rated negative torque of the EM at the current speed
- The maximum available negative torque from the EM, according to limits imposed by the capability of the battery.

For each candidate operating point, calculate the constituent factors for optimization:

The following steps are involved in this step:

- Calculate the fuel energy that would be consumed by the ICE. The actual fuel energy consumed for a given ICE torque is affected by two things:
- Hot, steady state ICE fuel maps
- Temperature correction factors

MODIFIED POWER FOLLOWER

For a given torque request and motor torque, **equation 1** sets the ICE torque. At this torque and given speed, the ICE map provides the fuel consumed by the ICE when it is hot (**Figure 4**). A cold ICE uses more fuel than a hot ICE. A cold ICE correspondingly produces more emissions than a hot ICE. The outputs of the ICE for cold and hot operation are given by

$$Cold\_use = Hot\_use\left(K_1 + \left(\frac{95 - Temp_{ice}}{75}\right)^{K_2}\right)$$

$$Fuel\_use = Fuel\_hot\left(K_1 + \left(\frac{95 - Temp_{ice}}{75}\right)^{3.1}\right)$$

$$Cold\_use = Hot\_use\left(K_1 + \left(\frac{95 - Temp_{ice}}{75}\right)^{K_2}\right)$$

$$Fuel\_use = Fuel\_hot\left(K_1 + \left(\frac{95 - Temp_{ice}}{75}\right)^{3.1}\right)$$

1

MODIFIED POWER FOLLOWER

Calculate the effective fuel energy that would be consumed by EM for a time interval, for example 1 second using the following steps:

- Find fuel energy versus EM torque
- Find versus EM torque, accounting for gain due to regenerative braking SOC
- Combine the curves obtained in above steps
- Determine the equivalent energy by evaluating the curve from step3 at

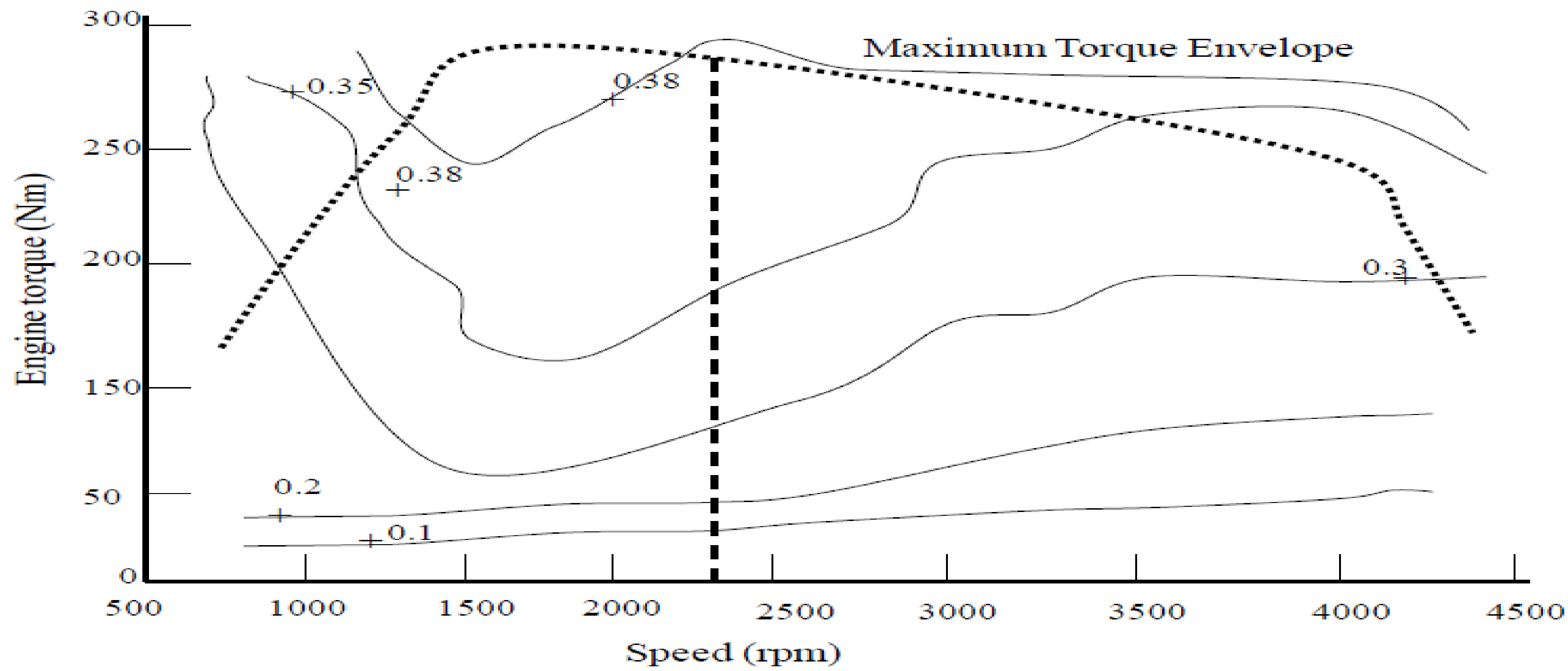


Figure 4: Efficiency map for hot ICE [1]

State Machine Based

The state machine dictates the operating mode of the HEV such:

- ENGINE (ICE propelling the vehicle)
- BOOSTING (both ICE and EM propelling the vehicle)
- CHARGING (ICE propelling the vehicle and charging the battery)

The transition between the operating modes is decided based on:

- the change in driver demand
- a change in vehicle operating condition
- a system or a subsystem fault.

State Machine Based

The various states involved in the control strategy are listed in **Table 1**

Table 1: States of an HEV

State	ICE	Clutch	EM	Description
Off	Off	Disengaged	Off	Vehicle off state
EM drive	Off	Disengaged	Motoring	EM propels the vehicle
Regeneration – Low velocity	Off	Disengaged	Generating	Regenerative Braking with ICE disconnected
Regeneration – High velocity	Off	Engaged	Generating	Regenerative Braking with ICE connected
ICE drive	On	Engaged	Off	ICE propelling the vehicle
Boost	On	Engaged	Motoring	ICE and EM propel the vehicle
Charging	On	Engaged	Generating	ICE propels the vehicle and charges the batteries
ICE Stop	Off	Disengaged	Motoring	Motor propelling the vehicle and ICE disconnected
ICE Start	On	Engaged	Motoring	Motor propelling the vehicle and starting the ICE
Bleed	On	Engaged	Motoring	ICE propelling the vehicle and motor discharging the battery

The Fuzzy Logic Based Control System

Fuzzy logic is an extension of the conventional rule-based methods and has following advantages over them:

- ***Robustness*** **:** It is inherently robust because it does not require precise, noise free inputs and the output is a smooth function despite a wide range of input variations.
- ***Adaptation*** **:** Since FLC processes user defined rules governing the system, it can be modified easily to improve or drastically alter system performance.

Fuzzy Logic in Design of Controllers:

The energy management and control strategy using FLC performs following actions:

- maximizes fuel economy, minimize emissions and distribute the driver's request for power between two sources: ***ICE*** and ***Motor*** .
- maximize fuel economy at any point in operation, that is, provide dynamic or instantaneous optimization.
- maximize some other attributes such as acceleration of vehicle

The Fuzzy Logic Based Control System

Fuzzy Logic in Design of Controllers:

In **Figure 1** the generic schematic diagram of FLC is shown. The four components of FLC, as shown in **Figure 1** , are:

- Fuzzification, which is the change from crisp values to fuzzy values. For ICE speed, the crisp value may be 2000rpm and a possible rule for ICE speed may be “If ICE rpm is too low, then inject more fuel”. The fuzzy value associated with the “If X, then Z” statement would be for X<2000 rpm.

The Fuzzy Logic Based Control System

Fuzzy Logic in Design of Controllers:

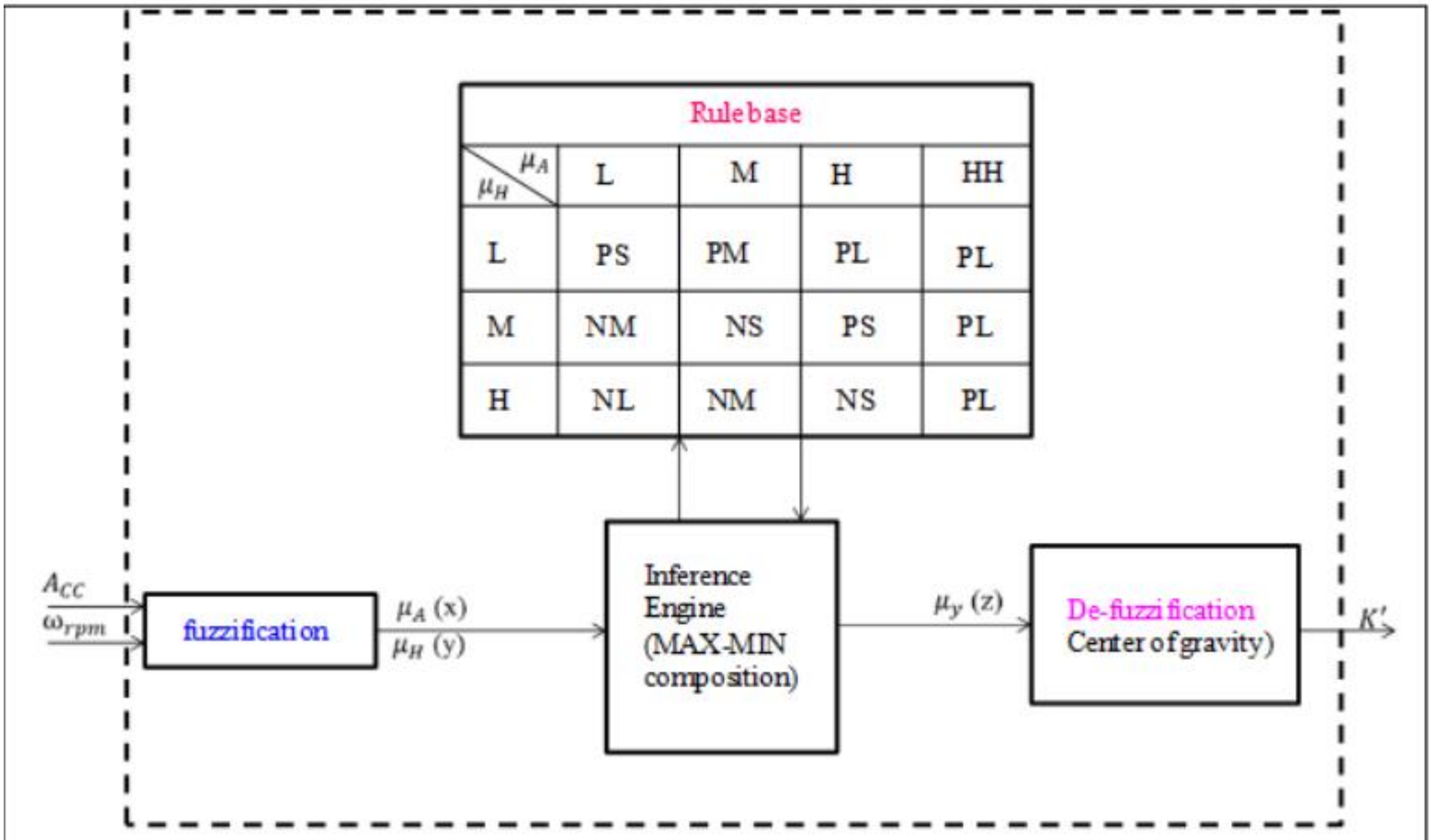


Fig.1: Generic block diagram of FLC [1]

The Fuzzy Logic Based Control System

Fuzzy Strategy:

The FLC, explained in this section, satisfies the following objectives:

- minimize NOx emissions
- sustain battery SOC
- achieve desired torque requested by the driver
- The inputs to this FLC are:
- Acceleration pedal stroke (Acc)
- EM speed (ω_{em})
- An induction motor (IM) used in the drivetrain and the IM is directly coupled to the ICE. Since the IM is directly coupled to the diesel ICE, it will be in the field weakening region in most of the ICE operating, the generating torque decreases as the ICE speed increases.

The Fuzzy Logic Based Control System

Fuzzy Strategy:

Some basic principles of generating the torque command from the acceleration pedal stroke and ICE rotational speed in the HEV can be described as follows:

Low ICE Speed: When the ICE rotational speed is low, it generates pollutant emissions with low efficiency. Hence, in this operating condition, the torque assistant control by the IM should be performed. Assistant torque is commanded to increase in proportion to the acceleration pedal stroke as in the conventional ICE vehicle, that is:

Medium ICE Speed: When the diesel ICE's speed is medium, it can supply sufficient torque to the hybrid drive train. Hence, battery recharging control is performed instead of torque assistance control when acceleration pedal stroke is below some extent.

Fuzzy Strategy:

High ICE Speed:

- When the diesel ICE speed is high, the torque assistance control is performed as that of the medium speed range.
- In battery recharging control the IM's output power is kept constant. Now since the ICE can produce more power than in the medium speed range, the factor *K* should be made to be negatively greater.

Fuzzy Strategy:

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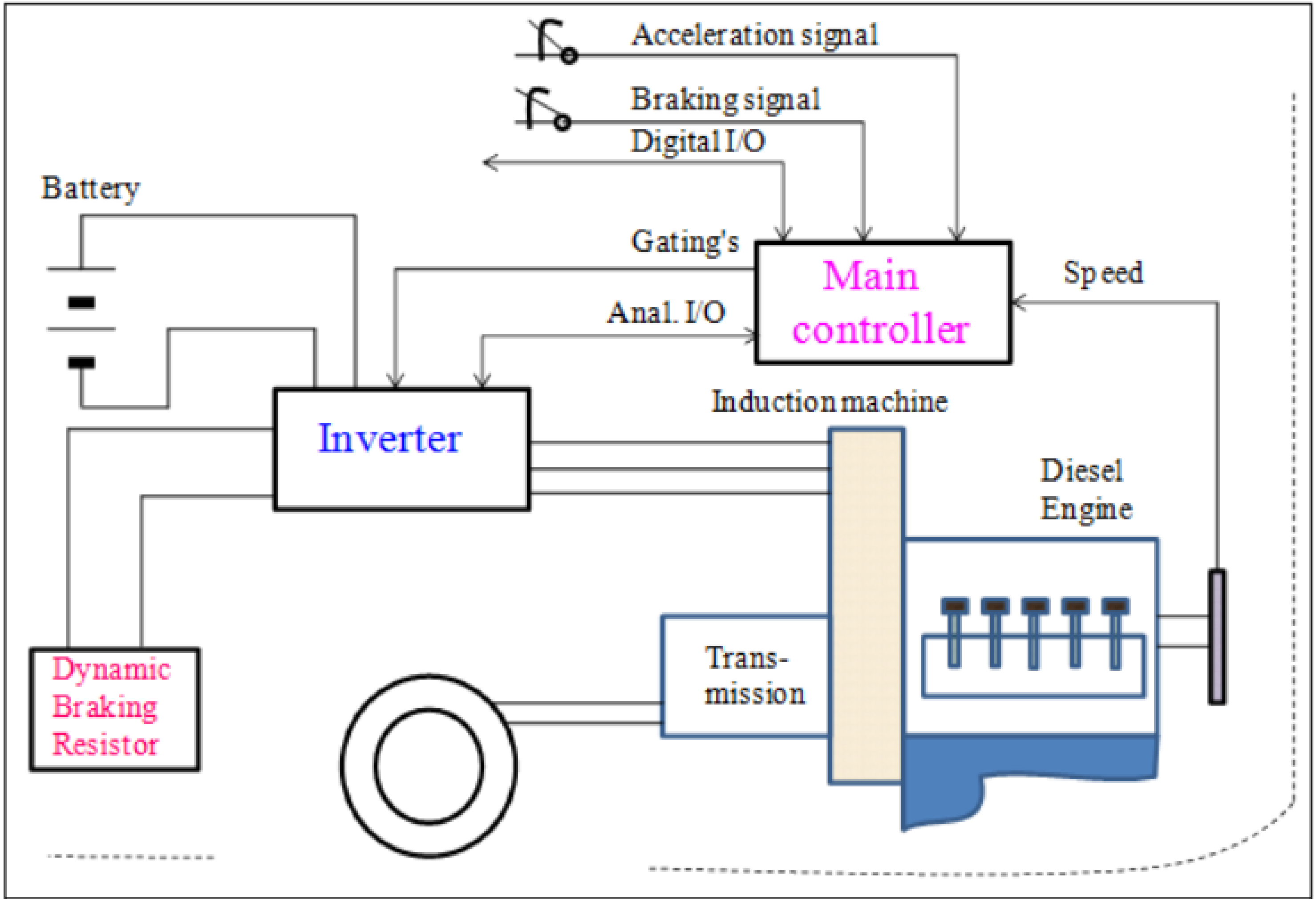

Fig.2: Drivetrain configuration [1]