UNIT – I

Introduction Conventional Vehicles

What are conventional engines?

In a conventional engine, **the reciprocating movement of the pistons has to be converted into a rotary movement in order to turn the crankshaft**. This is achieved by means of connecting rods that join the pistons to the crankshaft.

Which type of engines is used in cars?

There are mainly two types of car engines: **petrol and diesel**.

What is conventional combustion engine?

An internal combustion engine (ICE or IC engine) is **a heat engine in which the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit**.

What is a conventional vehicle?

Conventional vehicles **use an internal combustion engine fueled by gasoline or diesel to power the wheels**. Electricity is used for some accessories, but is not used to move the vehicle.

What is conventional diesel engine?

The diesel engine, named after Rudolf Diesel, is **an internal combustion engine in which ignition of the fuel is caused by the elevated temperature of the air in the cylinder due to mechanical compression**; thus, the diesel engine is a so-called compression-ignition engine (CI engine).

What are the 3 types of engines?

Types of engines and how they work

- Internal combustion engines (IC engines)
- External combustion engines (EC engines)
- Reaction engines.

What is the 2 main types of engine?

Engines are of two types, & these are **externals combustion engines and internal combustion engines**. External combustion engine:- In externals combustion engines, the combustion of fuel takes place outside the engines—for example, the steam engine.

Which type of engine is best for cars?

These are the 12 best car engines from 1999 to 2018*

- 8: Mazda Renesis Rotary. ...
- 7: BMW 3.0-litre twin-turbo. ...
- 6: BMW 1.5-litre petrol-electric hybrid. ...
- 5: Toyota 1.5-litre Hybrid Synergy Drive. ...
- 4: Volkswagen 1.4-litre TSI twin-charger. ...
- 3: BMW M 3.2-litre straight-six. ...
- 2: Ford 1.0-litre EcoBoost. ...
- 1: Ferrari 3.9-litre twin-turbo V8.

An **internal combustion engine** (**ICE** or **IC engine**) is a heat engine in which the combustion of a fuel occurs with an oxidizer (usually air) in a combustion chamber that is an integral part of the working fluid flow circuit.

In an internal combustion engine, the expansion of the high-temperature and high-pressure gases produced by combustion applies direct force to some component of the engine.

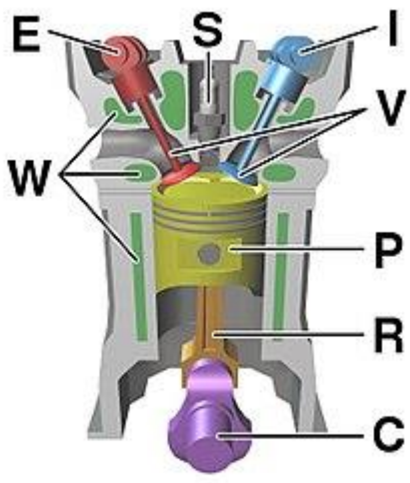
The force is typically applied to pistons (piston engine), turbine blades (gas turbine), a rotor (Wankel engine), or a nozzle (jet engine).

This force moves the component over a distance, transforming chemical energy into kinetic energy which is used to propel, move or power whatever the engine is attached to.

This replaced the external combustion engine for applications where the weight or size of an engine was more important.[1][2][3]

Diagram of a cylinder as found in an overhead cam 4-stroke gasoline engine:

- **C** – crankshaft
- **E** – exhaust camshaft
- **I** – inlet camshaft
- **P** – piston
- **R** – connecting rod
- **S** – spark plug
- **V** – valves. red: exhaust, blue: intake.
- **W** – cooling water jacket



HOW DOES AN INTERNAL COMBUSTION ENGINE WORK?

Combustion, also known as burning, is the basic chemical process of releasing energy from a fuel and air mixture.

In an internal combustion engine (ICE), the ignition and combustion of the fuel occurs within the engine itself.

The engine then partially converts the energy from the combustion to work.

The engine consists of a fixed cylinder and a moving piston.

The expanding combustion gases push the piston, which in turn rotates the crankshaft. Ultimately, through a system of gears in the powertrain, this motion drives the vehicle’s wheels.

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Internal Combustion Engine
The internal combustion engine is an engine in which the combustion of a fuel (normally a fossil fuel) occurs with an oxidizer (usually air) in a combustion chamber.2 – Stroke EngineRotay Engine4 – Stroke Engine

External Combustion Engine
An external combustion engine (EC engine) is a heat engine where an (internal) working fluid is heated by combustion in an external source, through the engine wall or a heat exchanger. The fluid then, by expanding and acting on the mechanism of the engine, produces motion and usable work. The fluid is then cooled, compressed and reused (closed cycle), or (less commonly) dumped, and cool fluid pulled in (open cycle air engine).Jet Engine Locomotives engine

Reciprocating Engine INTERNAL COMBUSTION ENGINE
A reciprocating engine, also often known as a piston engine, is a heat engine that uses one or more reciprocating pistons to convert pressure into a rotating motion. This article describes the common features of all types. The main types are: the internal combustion engine, used extensively in motor vehicles; the steam engine, the mainstay of the Industrial Revolution; and the niche application Stirling engine.Stirling Engine4 Stroke Engine2 Stroke Engine

Rotary Engine

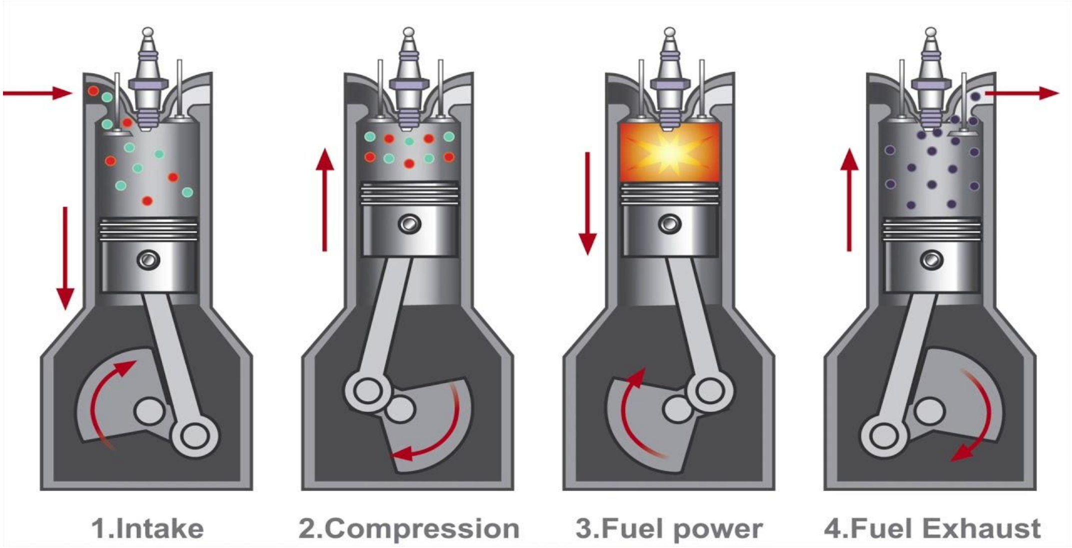
A rotary engine is essentially a standard Otto cycle engine, but instead of having a fixed cylinder block with rotating crankshaft as with a conventional radial engine, the crankshaft remains stationary and the entire cylinder block rotates around it. In the most common form, the crankshaft was fixed solidly to an aircraft frame, and the propeller simply bolted onto the front of the crankcase.

1st Stroke = INTAKE stroke = 180° of crankshaft revolution
Top Dead Centre (TDC)

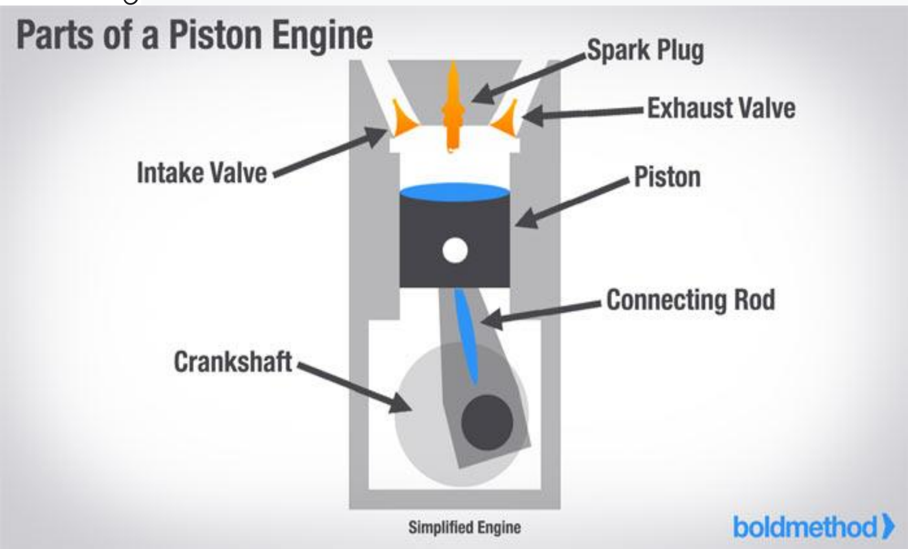
4th Stroke = INTAKE stroke = 720° of crankshaft revolution

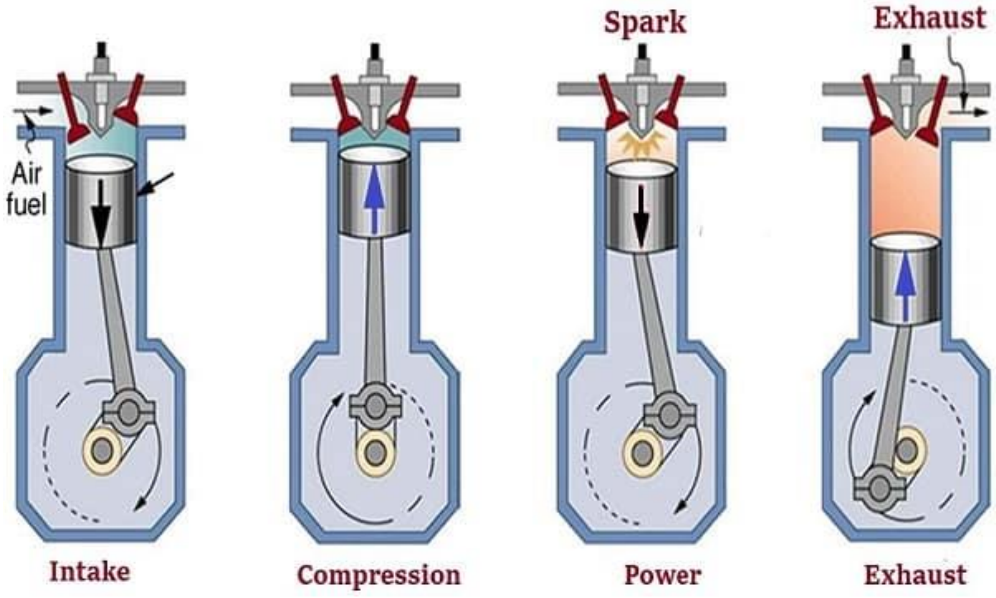
2nd Stroke = INTAKE stroke = 360° of crankshaft revolution Bottom Dead Centre (BDC)

3rd Stroke = INTAKE stroke = 540° of crankshaft revolution



1. తీసుకోవడం
2. కుదింపు
3. ఇంధన శక్తి
4. అలిసిపోవు





What are vehicle performance parameters?

Vehicle Performance Parameters:

1. Fuel Economy 2. Acceleration 3. Top Speed 4. Ride Comfort 5.
What are the three basic performance capabilities of vehicles?

The three basic performance capabilities of automobiles which you will have control over are: (1) **acceleration and speed, (2) directional control and cornering, and (3) deceleration and braking**.

Vehicle performance Parameters
Maximum speed of vehicle
Gradient climbing
Acceleration
Steering
Terrain negotiation
Tilt negotiation
Braking
Reverse motion

What is vehicle performance?

Vehicle performance is the study of the motion of a vehicle.

The motion of any vehicle depends upon all the forces and moments that act upon it.

These forces and moments, for the most part are caused by interaction of the vehicle with the surrounding medium(s) such as air or water (e.g. fluid static and dynamic forces), gravitational attraction (gravity forces),

Earth's surface (support, ground, or landing gear forces), and on-board energy consuming devices such as rocket, turbojet, piston engine and propellers (propulsion forces).

Consequently, in order to fully understand the performance problem, it is necessary to study and, in some way, characterize these interacting forces.

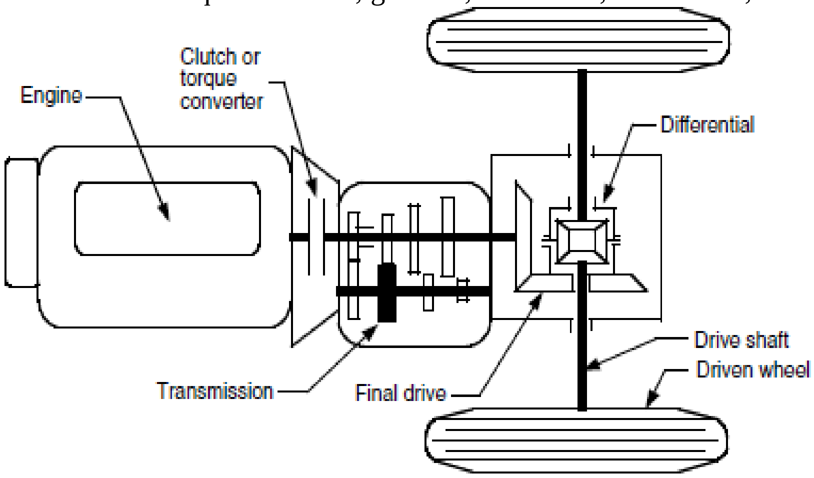
Some of the domains to be tested and analysed as part of the vehicle performance attributes include:

- Fuel economy & emissions
- Thermal and energy management
- NVH and acoustics, pass-by-noise regulation
- Durability
- Drivability
- Driving dynamics
- Integrated safety
- Aerodynamic performance
- Water management

VEHICLE POWER SOURCE CHARACTERIZATION:

An automotive power train, as shown in Figure 2.8, consists of a power plant (engine or electric motor), a clutch in manual transmission or a torque converter in automatic transmission, a gearbox (transmission)

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



The clutch is used in manual transmission to couple the gearbox to or decouple it from the power plant. The torque converter in automatic transmission is a hydrodynamic device, functioning as the clutch in manual transmission with a continuously variable gear ratio.

The gearbox supplies a few gear ratios from its input shaft to its output shaft for the power plant torque– speed profile to match the requirements of the load.

The final drive is usually a pair of gears that supply a further speed reduction and distribute the torque to each wheel through the differential.

The torque on the driven wheels, transmitted from the power plant, is expressed as

$$T_w = i_g i_0 \eta_t T_p$$

Where *ig* is the gear ratio of the transmission defined as *ig_ Nin/Nout* (*Nin* —input rotating speed, *Nout* — output rotating speed), *i*0 is the gear ratio of the final drive, η*t* is the efficiency of the driveline from the power plant to the driven wheels, and *Tp* is the torque output from the power plant.

The tractive effort on the driven wheels, as shown in Figure 1.6, can beexpressed as

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

Substituting (eq1) into (eq2) yields the following result

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

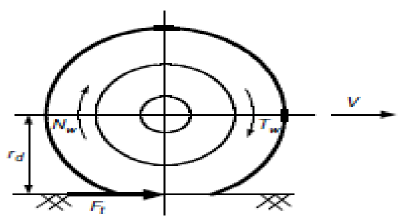


Figure 1: Tractive effort and torque on a driven wheel

The friction in the gear teeth and the friction in the bearings create losses in mechanical gear transmission. The following are representative values of the mechanical efficiency of various components:
Clutch: 99%
Each pair of gears: 95–97%
Bearing and joint: 98–99%
The total mechanical efficiency of the transmission between the engine output shaft and drive wheels or sprocket is the product of the efficiencies of all the components in the driveline. As a first approximation, the following average values of the overall mechanical efficiency of a manual gear-shift transmission may be used:
Direct gear: 90%
Other gear: 85%
Transmission with a very high reduction ratio: 75–80%
The rotating speed (rpm) of the driven wheel can be expressed as

$$N_w = \frac{N_p}{i_g i_0},$$

Where *Np* is the output rotating speed (rpm). The translational speed of the wheel center (vehicle speed) can be expressed as

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

Substituting (eq4) into (eq5) yields

$$V = \frac{\pi N_p r_d}{30 i_g i_0} \text{(m/s)}$$

VEHICLE POWER PLANT AND TRANSMISSION CHARACTERISTICS:

There are two limiting factors to the maximum tractive effort of a vehicle. One is the maximum tractive effort that the tire–ground contact can support and the other is the tractive effort that the power plant torque with given driveline gear ratios can provide (equation [2.29]). The smaller of these two factors will determine the performance potential of the vehicle. For on-road vehicles, the performance is usually limited by the second factor.
In order to predict the overall performance of a vehicle, its power plant and transmission characteristics must be taken into consideration.

1.5.2 .2.POWER PLANT CHARACTERISTICS: For vehicular applications, the ideal performance characteristic of a power plant is the constant power output over the full speed range. Consequently, the torque varies with speed hyperbolically as shown in Figure 1.5.2.1.

At low speeds, the torque is constrained to be constant so as not to be over the maxim aim it ed by the adhesion between the tire–ground contact areas. This constant power characteristic will provide the vehicle with a high tractive effort at low speed, where demands for acceleration, drawbar pull, or grade climbing capability are high.
Since the internal combustion engine and electric motor are the most commonly used power plants for automotive vehicles to date, it is appropriate to review the basic features of the characteristics that are essential to predicating vehicle

performance and driveline design.
Representative characteristics of a gasoline engine in full throttle and an electric motor at full load are shown in Figure 1.5.2.2 and Figure 1.5.2.3, respectively.

The internal combustion engine usually has torque–speed characteristics far from the ideal performance characteristic required by traction. It starts operating smoothly at idle speed.
Good combustion quality and maximum engine torque are reached at an intermediate engine speed. As the speed increases further, the mean effective pressure decreases because of the growing losses in the air- induction manifold and a decline in engine torque.
Power output, however, increases to its maximum at a certain high speed. Beyond this point, the engine torque decreases more rapidly with increasing speed. This results in the decline of engine power output. In vehicular applications, the maximum permissible

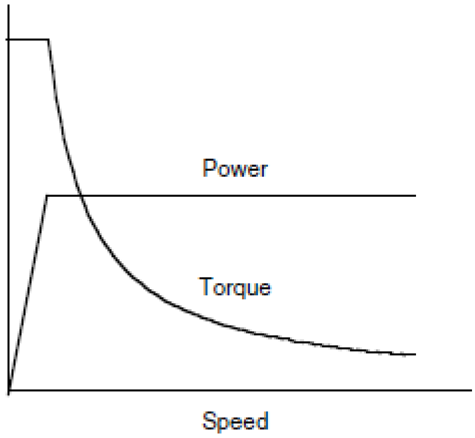


Figure1.5.2.1: Ideal performance characteristics for a vehicle traction power plant

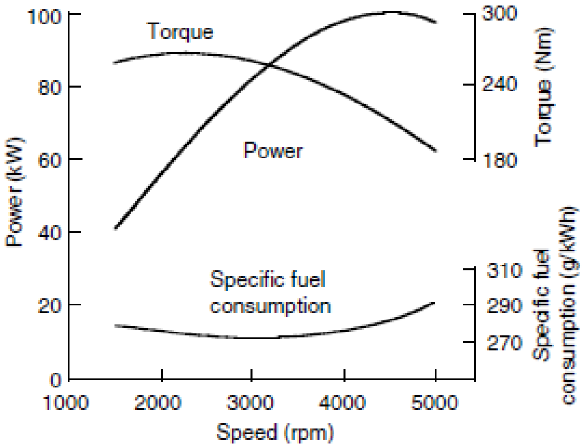


Figure1.5.2.2: Typical performance characteristics of gasoline engines

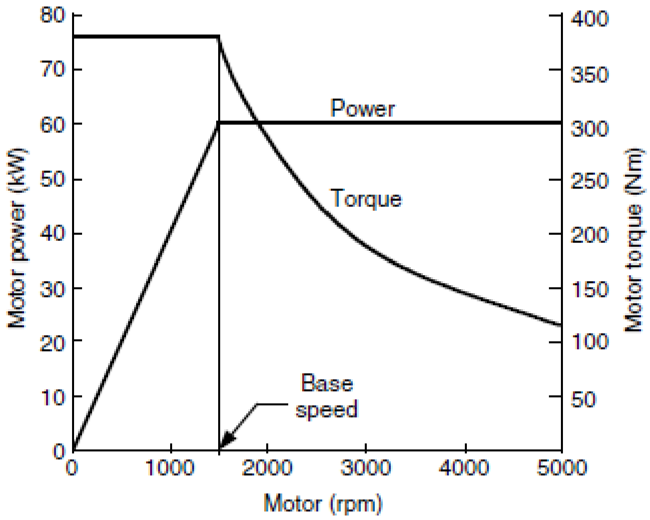


Figure1.5.2.3: Typical performance characteristics of electric motors for traction

Speed of the engine is usually set just a little above the speed of the maximum power output. The internal combustion engine has a relatively flat torque–speed profile (compared with an ideal one), as shown in Figure1.5.2.1.Consequently, a multi gear transmission is usually employed to modify it, as shown in Figure 1.5.2.3.Electric motors, however, usually have a speed–torque characteristic that is much closer to the ideal, as shown in Figure 1.5.2.2. Generally, the electric motor starts from zero speed.

As it increases to its base speed, the voltage increases to its rated value while the flux remains constant. Beyond the base speed, the

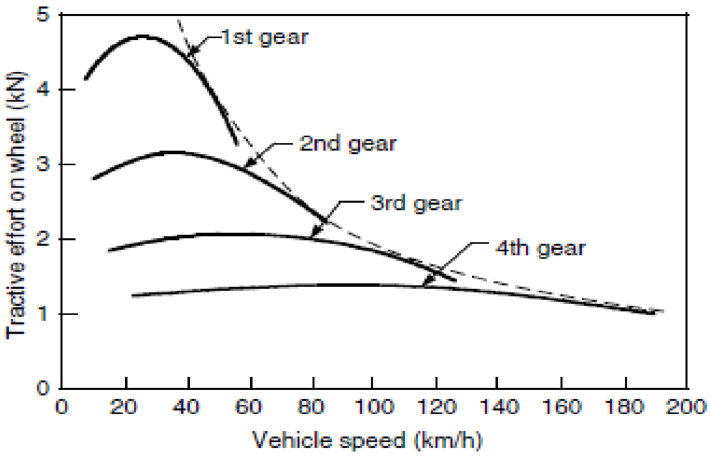


Figure 1.5.2.4: Tractive effort of internal combustion engine and a multi gear transmission vehicle vs. vehicle speed

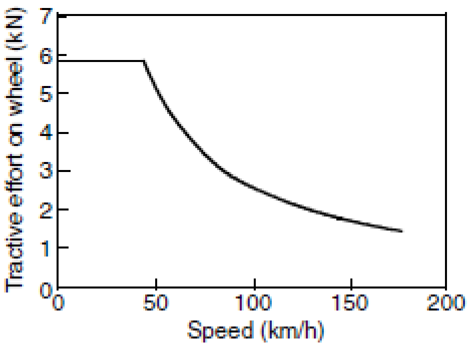


Figure1.5.2.5: Tractive effort of a single-gear electric vehicle vs. vehicle speed

Voltage remains constant and the flux is weakened. This results in constant output power while the torque declines hyperbolically with speed. Since the speed–torque profile of an electric motor is close to the ideal, a single-gear or double-gear transmission is usually employed, as shown in Figure 1.5.2.5.

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.

For automobile applications, there are usually two basic types of transmissions: manual gear transmission and hydrodynamic transmission.

1.5.3.1 Manual Gear Transmission

Manual gear transmission consists of a clutch, gearbox, final drive, and driveshaft. The final drive has a constant gear reduction ratio or a differential gear ratio. The common practice of requiring direct drive (non- reducing) in the gearbox to be in the highest gear determines this ratio.

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

In the first iteration, gear ratios between the highest and the lowest gear may be selected in such a way that the engine can operate in the same speed range for all the gears. This approach would benefit the fuel economy and performance of the vehicle. For instance, in normal driving, the proper gear can be selected according to vehicle speed to operate the engine in its optimum speed range for fuel-saving purposes. In fast acceleration, the engine can be operated in its speed range with high power output. This approach is depicted in Figure 1.5.3.2.For a four-speed gear box, the following relationship can be established.

And

$$K_g = \sqrt[3]{\frac{i_{g1}}{i_{gg4}}},$$

Where i_{g1}, i_{g2}, i_{g3}, and i_{g4} are t the first, second, third, and fourth gear, respectively. In a more general case, if the ratio of the highest

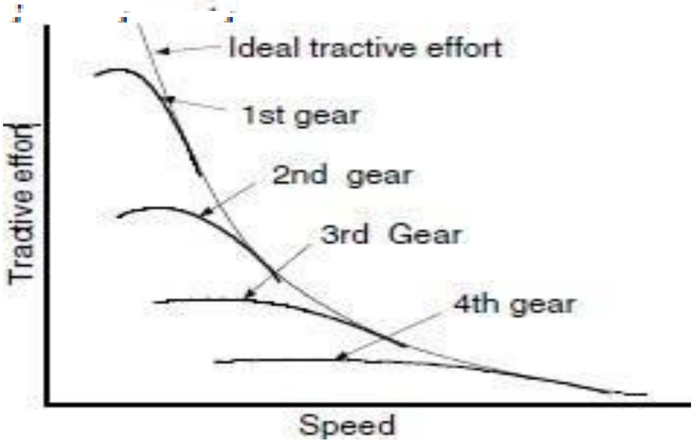


Figure1.5.3.1: Tractive effort characteristics of a gasoline engine-powered vehicle

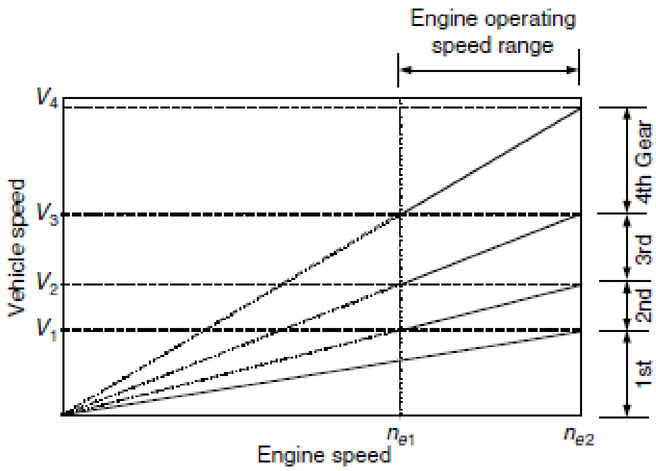


Figure1.5.3.2: Demonstration of vehicle speed range and engine speed range for each gear gear, *ign*(smaller gear ratio), and the ratio of the lowest gear, *ig*1 (largest gear ratio), have been determined and the number of the gear *ng* is known, the factor *Kg* can be determined as

$$K_g = \left(\frac{i_{g1}}{i_{gn}}\right)^{\frac{1}{(n_t-1)}},$$

And each gear ratio can be obtained by

$$i_{gn-1} = K_g\, i_{gn}$$
$$i_{gn-2} = K_g^2\, i_{gn}$$
$$\vdots$$
$$i_{g2} = K_g^{n_t-1}\, i_{gn}.$$

For passenger cars, to suit changing traffic conditions, the step between the ratios of the upper two gears is often a little closer than that based on (eq4).That is,

$$\frac{i_{g1}}{i_{g2}} > \frac{i_{g2}}{i_{g3}} > \frac{i_{g3}}{i_{g4}}.$$

This, in turn, affects the selection of the ratios of the lower gears. For commercial vehicles, however, the gear ratios in the gearbox are often arranged based on (eq5)Figure 1.5.3.3 shows the tractive effort of a gasoline engine vehicle with four gear transmission and that of an electric vehicle with single-gear transmission. It is clear that electric machines with favorable torque–speed characteristics can satisfy tractive effort with simple single-gear transmission.

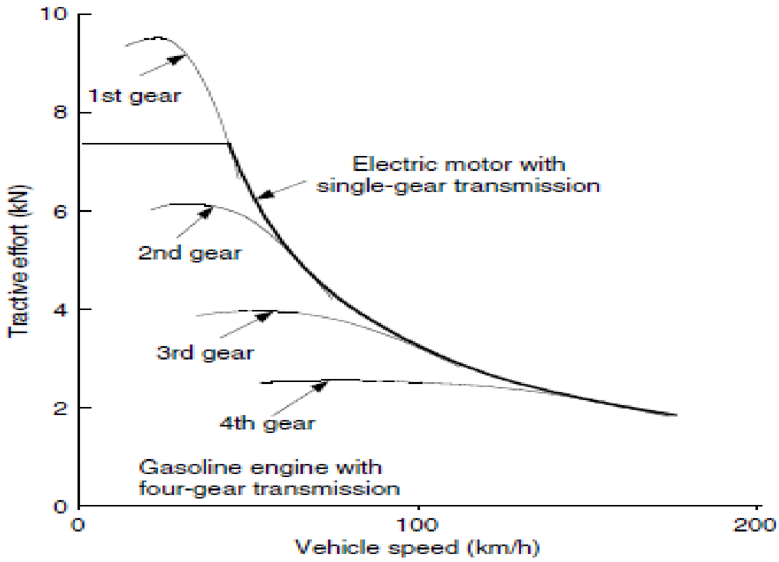


Figure1.5.3.3: Tractive efforts of a gasoline engine vehicle with four-gear gear transmission and an electric vehicle with single-transmission

Rolling resistance is **the combination of forces that work against the forward motion of your vehicle**. The weight of the vehicle, gravity and inertia, the amount of friction between the tires and the road surface, and air drag all play a part.

Rolling resistance is one of the forces that act to oppose the motion of a cyclist. It is caused mainly because of **deformation of the tyre** and can be understood by thinking about: energy losses due to heat (hysteresis) the forces pushing on the tyre.

One way to reduce rolling resistance is to **increase air pressure in your tires to the recommended amount**. With increased tire pressure, the tire ends up getting less deformed while going down the road, resulting in less energy wasted.

Rolling resistance, sometimes called rolling friction or rolling drag, is the force resisting the motion when a body (such as a ball, tire, or wheel) rolls on a surface.

Tractive effort is defined as **the force at the rims or the outer edges of the driving wheels of moving trains**. In other words, it is the sum of the tractive force and rolling effort on the road surface.

What is tractive effort in electric vehicle?

UNIT – II

INTRODUCTION TO HYBRID ELECTRIC VEHICLES

Hybrid electric vehicle (HEV):

The hybrid electric vehicle combines a gasoline engine with an electric motor. An alternate is a diesel engine and an electric motor.

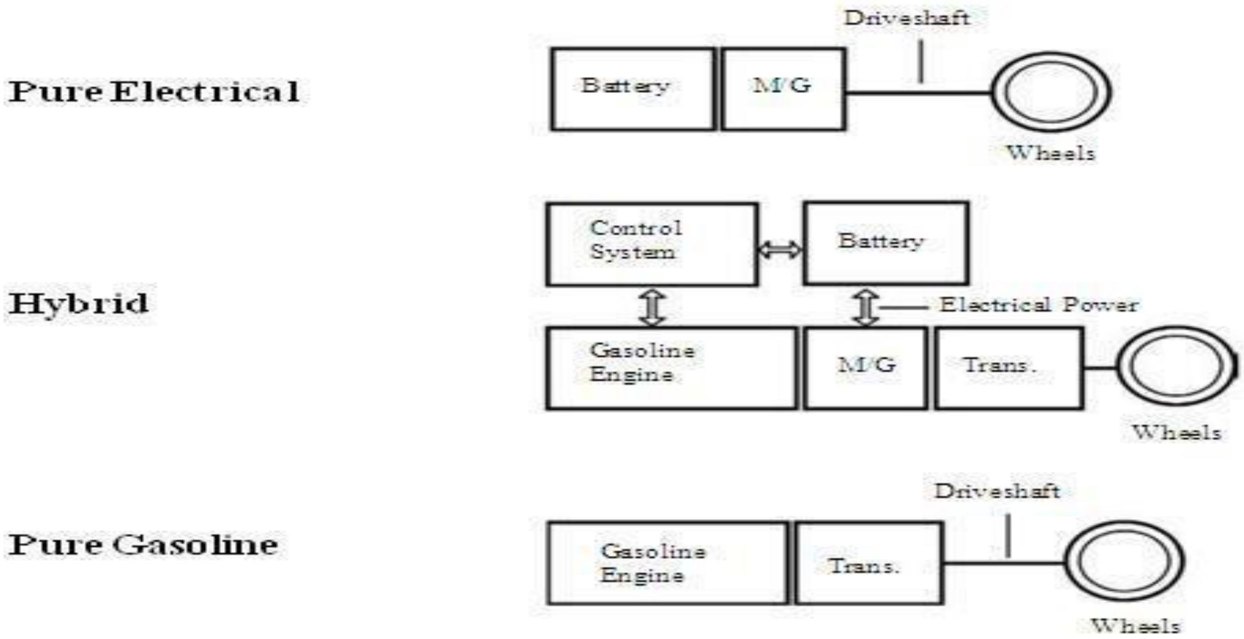


Figure 1: Components of a hybrid Vehicle that combines a pure gasoline with a pure EV.

As shown in **Figure 1**, a HEV is formed by merging components from a pure electrical vehicle and a pure gasoline vehicle. The Electric Vehicle (EV) has an M/G which allows regenerative braking for an EV; the M/G installed in the HEV enables regenerative braking. For the HEV, the M/G is tucked directly behind the engine. In Honda hybrids, the M/G is connected directly to the engine.

The transmission appears next in line. This arrangement has two torque producers; the M/G in motor mode, M-mode, and the gasoline engine. The battery and M/G are connected electrically.

HEVs are a combination of electrical and mechanical components. Three main sources of electricity for hybrids are batteries, FCs, and capacitors. Each device has a low cell voltage, and, hence, requires many cells in series to obtain the voltage demanded by an HEV. Difference in the source of Energy can be explained as:

- The FC provides high energy but low power.
- The battery supplies both modest power and energy.
- The capacitor supplies very large power but low energy.

The components of an electrochemical cell include anode, cathode, and electrolyte (shown in fig2). The current flow both internal and external to the cell is used to describe the current loop.

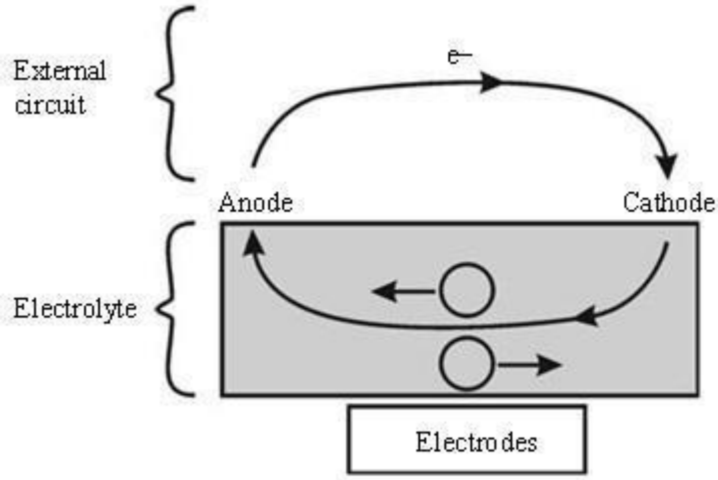


Figure 2: An electrode, a circuit for a cell which is converting chemical energy to electrical energy. The motion of negative charges is clockwise and forms a closed loop through external wires and load and the electrolyte in the cell.

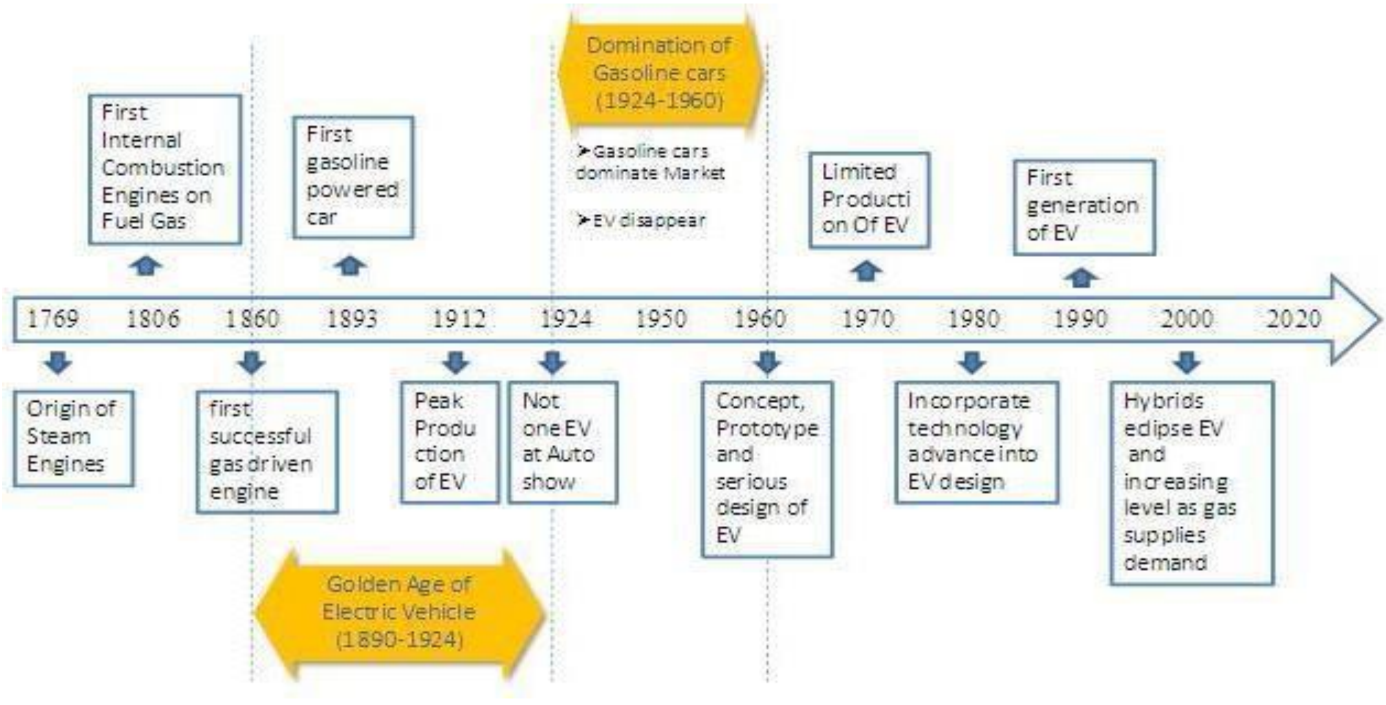
A critical issue for both battery life and safety is the precision control of the Charge/Discharge cycle. Overcharging can be traced as a cause of fire and failure. Applications impose two boundaries or limitations on batteries. The first limit, which is dictated by battery life, is the minimum allowed State of Charge. As a result, not all the installed battery energy can be used. The battery feeds energy to other electrical equipment, which is usually the inverter. This equipment can use a broad range of input voltage, but cannot accept a low voltage. The second limit is the minimum voltage allowed from the battery

HISTORY OF ELECTRIC VEHICLES:

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. Later, Steam condensers were applied to the steam car to solve the feed water problem. However, by that time Gasoline cars had won the marketing battle.

Gasoline cars of 1900 were noisy, dirty, smelly, cantankerous, and unreliable. In comparison, electric cars were comfortable, quiet, clean, and fashionable. Ease of control was also a desirable feature. Lead acid batteries were used in 1900 and are still used in modern cars. Hence lead acid batteries have a long history (since 1881) of use as a viable energy storage device. Golden age of ***Electrical vehicle*** marked from 1890 to 1924 with peak production of electric vehicles in 1912. However, the range was limited by energy storage in the battery. After every trip, the battery required recharging. At the 1924 automobile show, no electric cars were on display. This announced the end of the Golden Age of electric-powered cars.

The range of a ***gasoline car*** was far superior to that of either a steam or an electric car and dominated the automobile market from 1924 to 1960. The gasoline car had one dominant feature; it used gasoline as a fuel. The modern period starts with the oil embargoes and the gasoline shortages during the 1970s which created long lines at gas stations. Engineers recognized that the good features of the gasoline engine could be combined



with those of the electric motor to produce a superior car. A marriage of the two yields the hybrid automobile.

Figure 3: Historical development of automobile and development of interest and activity in the EV from 1890 to present day. Electric Vehicle merged into hybrid electric vehicle.

1769:

The first steam-powered vehicle was designed by Nicolas-Joseph Cugnot and constructed by M. Brezin that could attain speeds of up to 6 km/hour. These early steam-powered vehicles were so heavy that they were only practical on a perfectly flat surface as strong as iron.

1807:

The next step towards the development of the car was the invention of the internal combustion engine. Francois Isaac de Rivaz designed the first internal combustion engine in, using a mixture of hydrogen and oxygen to generate energy.

1825:

British inventor Goldsworthy Gurney built a steam car that successfully completed an 85 mile round-trip journey in ten hours' time.

1839:

Robert Anderson of Aberdeen, Scotland built the first electric vehicle**.**

1860:

In, Jean Joseph Etienne Lenoir, a Frenchman, built the first successful two-stroke gas driven engine**.**

1886:

Historical records indicate that an electric-powered taxicab**,** using a battery with 28 cells and a small electric motor, was introduced in England.

1888:

Immisch& Company built a four-passenger carriage, powered by a one-horsepower motor and 24-cell battery, for the Sultan of the Ottoman Empire. In the same year, Magnus Volk in Brighton, England made a three-wheeled electric car. *1890 – 1910 (*Period of significant improvements in battery technology)

INVENTION OF HYBRID VEHICLES:

1890:

Jacob Lohner, a coach builder in Vienna, Austria, foresaw the need for an electric vehicle that would be less noisy than the new gas-powered cars. He commissioned a design for an electric vehicle from Austro-Hungarian engineer Ferdinand Porsche, who had recently graduated from the Vienna Technical College.

Porsche's first version of the electric car used a pair of electric motors mounted in the front wheel hubs of a conventional car. The car could travel up to 38 miles. To extend the vehicle's range, Porsche added a gasoline engine that could recharge the batteries, thus giving birth to the first hybrid, the ***Lohner-Porsche Elektromobil.***

EARLY HYBRID VEHICLES:

1900:

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

1915:

Woods Motor Vehicle manufacturers created the Dual Power hybrid vehicle, second hybrid car in market. Rather than combining the two power sources to give a single output of power, the Dual Power used an electric battery motor to power the engine at low speeds (below 25km/h) and used the gasoline engine to carry the vehicle from these low speeds up to its 55km/h maximum speed. While Porsche had invented the series hybrid, Woods invented the parallel hybrid.

1918:

The Woods Dual Power was the first hybrid to go into mass production. In all, some 600 models were built by. However, the evolution of the internal combustion engine left electric power a marginal technology

1960:

Victor Wouk worked in helping create numerous hybrid designs earned him the nickname of the –Godfather of the Hybrid‖. In 1976 he even converted a Buick Skylark from gasoline to hybrid.

1978:

Modern hybrid cars rely on the regenerative braking system. When a standard combustion engine car brakes, a lot of power is lost because it dissipates into the atmosphere as heat. Regenerative braking means that the electric motor is used for slowing the car and it essentially collects this power and uses it to help recharge the electric batteries within the car. This development alone is believed to have progressed hybrid vehicle manufacture significantly. The Regenerative Braking System, was first designed and developed in 1978 by David Arthurs. Using standard car components he converted an Opel GT to offer 75 miles to the gallon and many home conversions are done using the plans for this system that are still widely available on the Interne

MODERN PERIOD OF HYBRID HISTORY:

The history of hybrid cars is much longer and more involved than many first imagine. It is, however, in the last ten years or so that we, as consumers, have begun to pay more attention to the hybrid vehicle as a viable alternative to ICE driven cars. Whether looking for a way to save money on spiralling gas costs or in an attempt to help reduce the negative effects on the environment we are buying hybrid cars much more frequently.

1990:

Automakers took a renewed interest in the hybrid, seeking a solution to dwindling energy supplies and environmental concerns and created modern history of hybrid car

1993:

In USA, Bill Clinton's administration recognized the urgency for the mass production of cars powered by means other than gasoline. Numerous government agencies, as well as Chrysler, Ford, GM, and USCAR combined forces in the PNGV (Partnership for a New Generation of Vehicles), to create cars using alternative power sources, including the development and improvement of hybrid electric vehicles.

1997:

The Audi Duo was the first European hybrid car put into mass production and hybrid production and consumer take up has continued to go from strength to strength over the decades.

2000:

Toyota Prius and Honda Insight became the first mass market hybrids to go on sale in the United States, with dozens of models following in the next decade. The Honda Insight and Toyota Prius were two of the first mainstream Hybrid Electric Vehicles and both models remain a popular line.

2005:

A hybrid Ford Escape, the SUV, was released in 2005. Toyota and Ford essentially swapped patents with one another, Ford gaining a number of Toyota patents relating to hybrid technology and Toyota, in return, gaining access to Diesel engine patents from Ford.

PRESENT OF HYBRID ELECTRIC VEHICLES:

Toyota is the most prominent of all manufacturers when it comes to hybrid cars. As well as the specialist hybrid range they have produced hybrid versions of many of their existing model lines, including several Lexus (now owned and manufactured by Toyota) vehicles. They have also stated that it is their intention to release a hybrid version of every single model they release in the coming decade. As well as cars and SUVs, there are a select number of hybrid motorcycles, pickups, vans, and other road going vehicles available to the consumer and the list is continually increasing.

FUTURE OF HYBRID ELECTRICAL VEHICLE:

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

SOCIAL AND ENVIRONMENTAL IMPORTANCE OF HYBRID EECTRIC VEHICLES:

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. Amongst the most notable producers of these pollutants are automobiles, which are almost exclusively powered by internal combustion engines and spew out unhealthy emissions.

According to various reports, cars and trucks are responsible for almost 25% of CO_2 emission and other major transportation methods account for another 12%. With immense quantities of cars on the road today, pure combustion engines are quickly becoming a target of global warming blame. One potential alternative to the world's dependence on standard combustion engine vehicles are hybrid cars. Cost-effectiveness is also an important factor contributing to the development of an environment friendly transportation sector.

ENVIRONMENTAL IMPACT ANALYSIS*:*

All stages of the life cycle were considered, starting from

a. The extraction of natural resources to produce materials and

b. Ending with conversion of the energy stored on board the vehicle into mechanical energy for vehicle displacement and

c. Other purposes (heating, cooling, lighting, etc.).

In addition, vehicle production stages and end-of-life disposal contribute substantially when quantifying the life cycle environmental impact of fuel-propulsion alternatives.

The analysis were conducted on six vehicles, each was representative of one of the above discussed categories. The specific vehicles were:

1. Toyota Corolla (conventional vehicle),
2. Toyota Prius (hybrid vehicle),
3. Toyota RAV4EV (electric vehicle),
4. Honda FCX (hydrogen fuel cell vehicle),
5. Ford Focus H_2 -ICE (hydrogen ICE vehicle),
6. Ford Focus H_2 -ICE adapted to use ammonia as source of hydrogen (ammonia-fuelled ICE vehicle).

Two environmental impact elements were accounted for in the:

a. Air pollution (AP) and

b. Greenhouse gas (GHG) emissions

The main GHGs were CO_2,CH_4, N_2O, and SF_6 (sulphur hexafluoride), which have GHG impact weighting coefficients relative to CO_2 of 1, 21, 310, and 24,900, respectively.

For AP, the airborne pollutants CO, NO_X,SO_X, and VOCs are assigned the following weighting coefficients: 0.017, 1, 1.3, and 0.64, respectively.

The vehicle production stage contributes to the total life cycle environmental impact through the pollution associated with

a. The extraction and processing of material resources,

b. Manufacturing and

c. The vehicle disposal stage.

Additional sources of GHG and AP emissions were associated with the fuel production and utilization stages. The environmental impacts of these stages have been evaluated in numerous life cycle assessments of fuel cycles.

Regarding electricity production for the electric car case, three case scenarios were considered here:

1. When electricity is produced from renewable energy sources and nuclear energy;

2. When 50% of the electricity is produced from renewable energy sources and 50% from natural gas at an efficiency of 40%;
3. When electricity is produced from natural gas at an efficiency of 40%.

AP emissions were calculated assuming that GHG emissions for plant manufacturing correspond entirely to natural gas combustion. GHG and AP emissions embedded in manufacturing a natural gas power generation

Electricity-generation scenario	Description of Electricity generation Scenario	GHG emission (g)	AP emission (g)
1	Electricity produced = 100% (Renewable Energy + Nuclear Energy)	5.11	0.195
2	Electricity produced = (50% Renewable Energy + 50% Natural gas)	77.5	0.296
3	Electricity produced = 100% Natural Gas	149.9	0.573

plant were negligible compared to the direct emissions during its utilization. Taking those factors into account, GHG and AP emissions for the three scenarios of electricity generation were presented in Table 2.

Table2: GHG and air pollution emissions per MJ of electricity produced

Hydrogen charging of fuel tanks on vehicles requires compression. Therefore, presented case considered the energy for hydrogen compression to be provided by electricity.

Table 3: GHG and air pollution emissions per MJ fuel of Hydrogen from natural gas produced

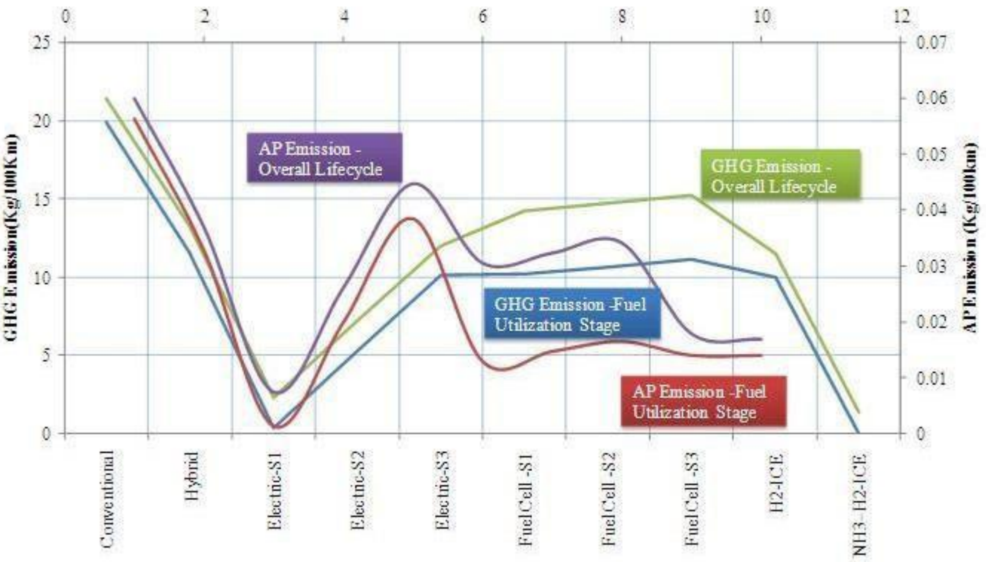
GHG and AP emissions were reported for hydrogen vehicles for the three electricity-generation scenarios considered (see table 3), accounting for the environmental effects of hydrogen compression.

Fuel	GHG emissions, g	AP emissions, g
Hydrogen from natural gas		
Scenario 1	78.5	0.0994
Scenario 2	82.1	0.113
Scenario 3	85.7	0.127

	Fuel utilization stage		Overall life cycle	
Vehicle type	GHG emissions	AP emissions	GHG emissions	AP emissions
	(kg/100 km)	(kg/100 km)	(kg/100 km)	(kg/100 km)
Conventional	19.9	0.0564	21.4	0.06
Hybrid	11.6	0.0328	13.3	0.037
Electric-S1	0.343	0.00131	2.31	0.00756
Electric-S2	5.21	0.0199	7.18	0.0262
Electric-S3	10.1	0.0385	12	0.0448
Fuel Cell -S1	10.2	0.0129	14.2	0.0306
Fuel Cell -S2	10.6	0.0147	14.7	0.0324
Fuel Cell -S3	11.1	0.0165	15.2	0.0342
H2-ICE	10	0.014	11.5	0.018
NH3–H2-ICE	0	0.014	1.4	0.017

Table 4. Environmental impact associated with vehicle Overall Life cycle and Fuel Utilization State.

The environmental impact of the fuel utilization stage, as well as the overall life cycle is presented in Table 4. The H2-ICE vehicle results were based on the assumption that the only GHG emissions during the utilization stage were associated with the compression work, needed to fill the fuel tank of the vehicle. The GHG effect of water vapor emissions was neglected in this analysis due its little value,. For the ammonia fuel vehicle, a very small amount of pump work was needed therefore, ammonia fuel was considered to emit no GHGs during fuel utilization.



ECONOMICAL ANALYSIS

A number of key economic parameters that characterize vehicles were:

a. Vehicle price,

b. Fuel cost, and

c. Driving range.

This case neglected maintenance costs; however, for the hybrid and electric vehicles, the cost of battery replacement during the lifetime was accounted for. The driving range determines the frequency (number and separation distance) of fuelling stations for each vehicle type. The total fuel cost and the total number of kilometers driven were related to the vehicle life (see Table 1).

Vehicle type	Fuel Type	Initial Price (USk$)	Specific fuel Price (US$/100 km)	Driving Range (Km)	Price of battery Changes During Vehicle Life cycle (USk$)
Conventional *(Toyota Corolla)*	Gasoline	15.3	2.94	540	1 x 0.1
Hybrid *(Toyota Prius)*	Gasoline	20	1.71	930	1 x 1.02
Electric *(Toyota RAV4EV)*	Electricity	42	0.901	164	2 x 15.4
Fuel cell *(Honda FCX)*	Hydrogen	100	1.69	355	1 x 0.1
H2-ICE *(Ford Focus H_2-ICE)*	Hydrogen	60	8.4	300	1 x 0.1
NH3–H2-ICE *(Ford Focus H_2-ICE and ammonia Adaptive)*	Ammonia	40	6.4	430	1 x 0.1

Table1: Technical and economical values for selected vehicle types

For the Honda FCX the listed initial price for a prototype leased in 2002 was USk$2,000, which is estimated to drop below USk$100 in regular production. Currently, a Honda FCX can be leased for 3 years with a total price of USk$21.6. In order to render the comparative study reasonable, the initial price of the hydrogen fuel cell vehicle is assumed here to be USk$100. For e electric vehicle, the specific cost was estimated to be US$569/kWh with nickel metal hydride (NiMeH) batteries which are typically used in hybrid and electric cars. Historical prices of typical fuels were used to calculate annual average price.

RESULTS OF TECHNICAL–ECONOMICAL–ENVIRONMENTAL ANALYSIS:

In present situation this case study provides a general approach for assessing the combined technical– economical–environmental benefits of transportation options.

This analysis showed that the hybrid and electric cars have advantages over the others. The economics and environmental impact associated with use of an electric car depends significantly on the source of the electricity:

- a. If electricity is generated from renewable energy sources, the electric car is advantageous to the hybrid vehicle.

  b. If the electricity is generated from fossil fuels, the electric car remains competitive only if the electricity is generated on-board.

  c. If the electricity is generated with an efficiency of 50–60% by a gas turbine engine connected to a high-capacity battery and electric motor, the electric car is superior in many respects.

  d. For electricity-generation scenarios 2 and 3, using ammonia as a means to store hydrogen onboard a vehicle is the best option among those analysed (as shown in figure 2).

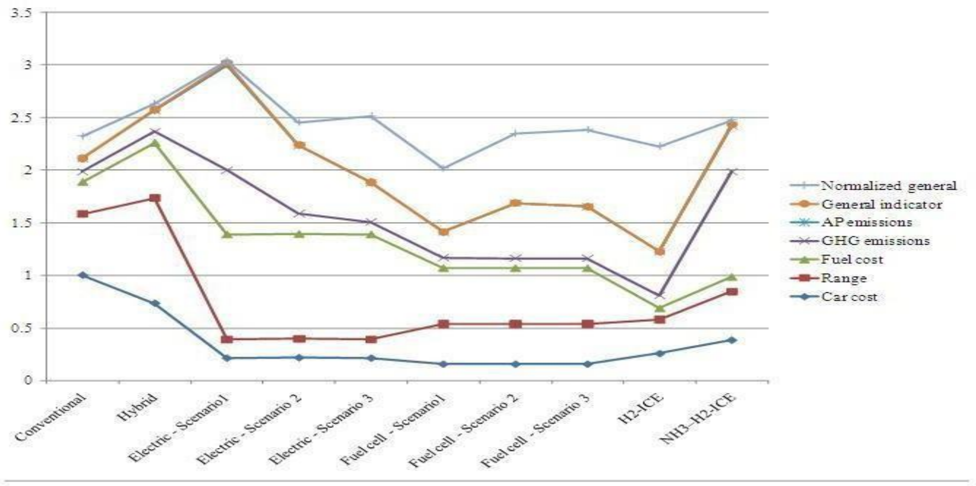


Figure2: Normalized economic and environmental indicators for six vehicle types

The electric car with capability for on-board electricity generation represents a beneficial option and is worthy of further investigation, as part of efforts to develop energy efficient and ecologically benign vehicles.

The main limitations of this study were as follows:

(i) The use of data which may be of limited accuracy in some instances;

(ii) The subjectiveness of the indicators chosen; and

(iii) The simplicity of the procedure used for developing the general indicator without using unique weighting coefficients.

Despite these limitations, the study reflects relatively accurately and realistically the present situation and provides a general approach for assessing the combined technical–economical–environmental benefits of transportation options.

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. This allows the ICE to operate only at speeds and loads where it is most efficient. When an HEV is stopped, rather than running the engine at idle, where it is extremely inefficient, the control system may either shut off the engine, with the storage device providing auxiliary power (for heating or cooling the vehicle interior, powering headlights, etc.), or run the engine at a higher-than-idle (more efficient) power setting and use the excess power (over auxiliary loads) to recharge the storage device. When the vehicle control system can shut the engine off at idle, the drivetrain can be designed so that the drive motor also serves as the starter motor, allowing extremely rapid restart due to the motor's high starting torque.

• **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. This depends, of course, on the storage mechanism chosen, the vehicle performance requirements, and so forth.

• **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. Further, some of the components may be forced to operate under conditions where they have reduced efficiency. For example, like ICEs, most electric motors have lower efficiency at the low-speed, low-load conditions often encountered in city driving. Without careful component selection and a control strategy that minimizes electric losses, much of the theoretical efficiency advantage often associated with an electric drive train can be lost.

HYDRODYNAMIC TRANSMISSION

Hydrodynamic transmissions use fluid to transmit power in the form of torque and speed and are widely used in passenger cars. They consist of a torque converter and an automatic gearbox. The torque converter consists of at least three rotary elements known as the impeller (pump), the turbine, and the reactor, as shown in Figure 2.18.

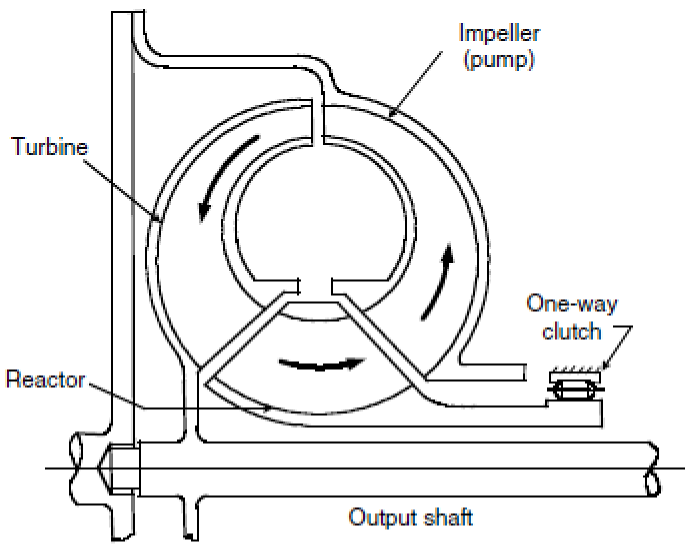
The impeller is connected to the engine shaft and the turbine is connected to the output shaft of the converter, which in turn is coupled to the input shaft of the multispeed gearbox. The reactor is coupled to external housing to provide a reaction on the fluid circulating in the converter. The function of the reactor is to enable the turbine to develop an output torque higher than the input torque of the converter, thus producing torque multiplication. The reactor is usually mounted on a free wheel (one-way clutch) so that when the starting period has been completed and the turbine speed is approaching that of the pump, the reactor is in free rotation. At this point, the converter operates as a fluid coupled with a ratio of output torque to input torque that is equal to 1.0.

The major advantages of hydrodynamic transmission may be summarized as follows:

• When properly matched, the engine will not stall.

• It provides flexible coupling between the engine and the driven wheels.

• Together with a suitably selected multispeed gearbox, it provides torque–speed characteristics that approach the ideal.



The major disadvantages of hydrodynamic transmission are its low efficiency in a stop–go driving pattern and its complex construction.
The performance characteristics of a torque converter are described in terms of the following four parameters:

1. *Speed ratio*:

$$C_{sr} = \frac{output\_speed}{input\_speed},$$

Which is the reciprocal of the gear ratio mentioned before.

2. *Torque ratio:*

$$C_{tr} = \frac{output\_torque}{input\_torque}.$$

3. Efficiency:

$$\eta_c = \frac{output\_speed \times output\_torque}{input\_speed \times input\_torque} = C_{sr}C_{tr}.$$

4. *Capacity factor (size factor):*

$$K_{tc} = \frac{speed}{\sqrt{torque}}.$$

The capacity factor, *Kc*, is an indicator of the ability of the converter to absorber transmit torque, which is proportional to the square of the rotary speed. Typical performance characteristics of the torque converter are shown in Figure 1.5.3.2.2, in which torque ratio, efficiency, and input capacity factor — that is the ratio of input speed to the square root of input torque — are plotted against speed ratio. The torque ratio has the maximum value at stall condition, where the output speed is zero. The torque ratio decreases as the speed ratio increases (gear ratio decreases) and the converter eventually acts as a hydraulic coupling with a torque ratio of 1.0. At this point, a small difference between the input and output speed exists because of the slip between the impeller (pump) and the turbine. The efficiency of the torque converter is zero at stall condition and increases with increasing speed ratio (decrease in the gear ratio). It reaches the maximum when the converter acts as a fluid coupling (torque ratio equal to 1.0).
To determine the actual operating condition of the torque converter, the engine operating point has to be specified because the engine drives the torque converter.
To characterize the engine operating condition for the purpose of determining the combined performance of the engine and the converter, an engine capacity factor, *Ke*, is introduced and defined as

$$K_e = \frac{n_e}{\sqrt{T_e}}.$$

Where *ne* and *Te* are engine speed and torque,respectively.
The variation of the capacity factor with speed for a typical engine is shown in Figure 1.5.3.2.3.
To achieve proper matching, the engine and the torque converter should have a similar range in the capacity factor.

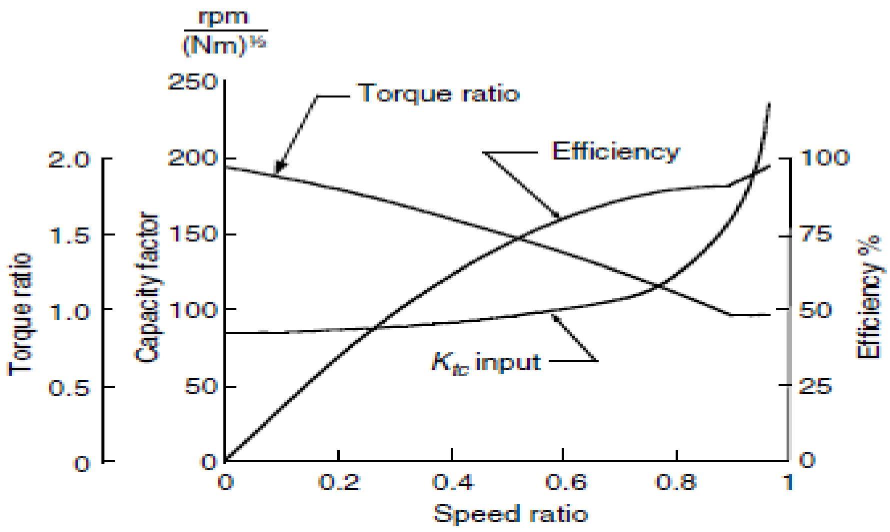


Figure 1.5.3.2.3.: Performance characteristics of a torque converter

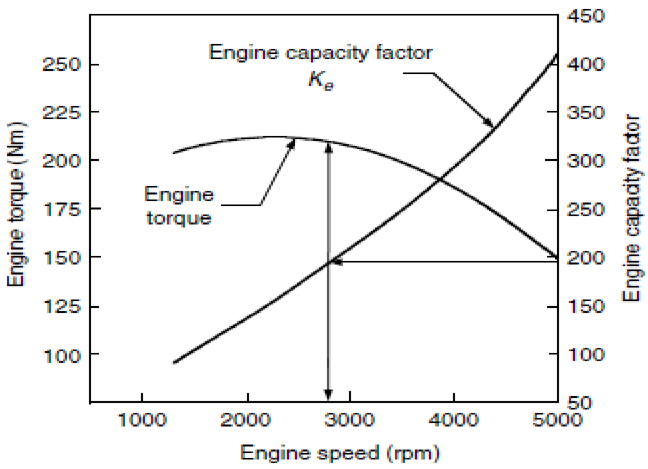


Figure 1.5.3.2.4: Capacity factor of a typical engine

The engine shaft is usually connected to the input shaft of the torque converter ,as mentioned above. That is,

$$K_e = K_c.$$

The matching procedure begins with specifying the engine speed and engine torque. Knowing the engine operating point, one can determine the engine capacity factor, Ke(see Figure 1.5.3.2.5). Since Ke_ Kc, the input capacity factor of the torque converter corresponding to the specific engine operating point is then known. As shown in Figure 1.5.3.2.4, for a particular value of the input capacity factor of the torque converter, Ktc, the converter speed ratio, Csr, and torque ratio, Ctr, can be determined from the torque converter performance characteristics. The output torque and output speed of the converter are then given by

$$T_{tc} = T_e C_{tr}$$

and

$$n_{tc} = n_e C_{sr},$$

Where *Ttc* and *nt c*are the output torque and output speed of the converter, Respectively.
Since the torque converter has a limited torque ratio range (usually less than 2), a multispeed gearbox is usually connected to it. The gearbox comprises several planetary gear sets and is automatically shifted. With the gear

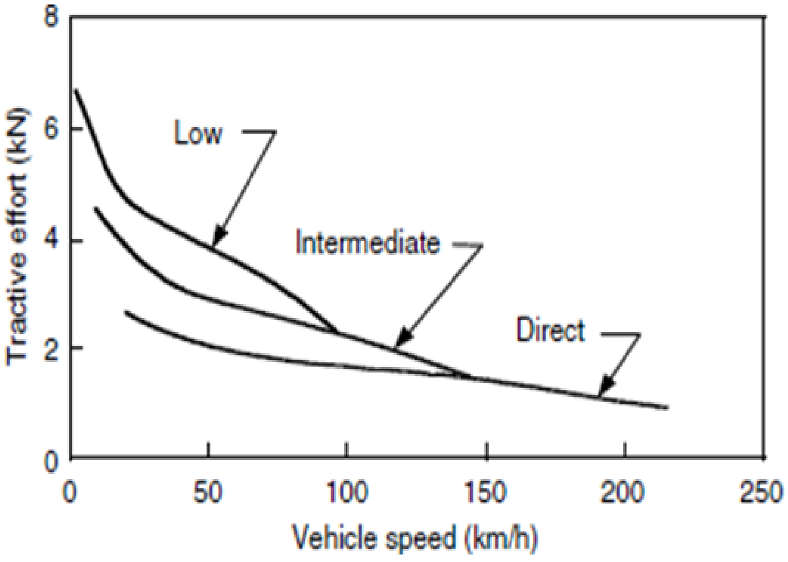


Figure 1.5.3.2.5.: Tractive effort–speed characteristics of a passenger car with automatic transmission

Ratios of the gearbox, the tractive effort and speed of the vehicle can be calculated by

$$F_t = \frac{T_e C_{tr} i_g i_0 \eta_t}{r}$$

and

$$V = \frac{\pi n_e C_{sr} r}{30 i_g i_0} (\mathrm{m/s}) = 0.377 \frac{n_e C_{sr} r}{i_t} (\mathrm{km/h}).$$

Above fig shows the variation of the tractive effort with speed for a passenger car equipped with a torque converter and a three-speed gearbox.

UNIT-III
ELECTRIC TRAINS

HYBRID ELECTRIC DRIVE TRAINS:

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. The other source of motive power can come from a number of different technologies, but is typically provided by an internal combustion engine designed to run on either gasoline or diesel fuel. As proposed by Technical Committee (Electric Road Vehicles) of the International Electro technical Commission, an HEV is a vehicle in which propulsion energy is available from two or more types of energy sources and at least one of them can deliver electrical energy. Based on this general definition, 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.

Most commonly, the propulsion force in HEV is provided by a combination of electric motor and an ICE. The electric motor is used to improve the energy efficiency (improves fuel consumption) and vehicular emissions while the ICE provides extended range capability.

Energy Savings Potential of Hybrid Drive trains

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 brake 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. This allows the ICE to operate only at speeds and loads where it is most efficient. When an HEV is stopped, rather than running the engine at idle, where it is extremely inefficient, the control system may either shut off the engine, with the storage device providing auxiliary power (for heating or cooling the vehicle interior, powering headlights, etc.), or run the engine at a higher-than-idle (more efficient) power setting and use the excess power (over auxiliary loads) to recharge the storage device. When the vehicle control system can shut the engine off at idle, the drivetrain can be designed so that the drive motor also serves as the starter motor, allowing extremely rapid restart due to the motor's high starting torque.

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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.

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HEV Configurations

In **Figure 2** the generic concept of a hybrid drivetrain and possible energy flow route is shown. The various possible ways of combining the power flow to meet the driving requirements are:

i. power train 1 alone delivers power
ii. power train 2 alone delivers power
iii. both power train 1 and 2 deliver power to load at the same time
iv. power train 2 obtains power from load (regenerative braking)
v. power train 2 obtains power from power train1
vi. power train 2 obtains power from power train 1 and load at the same time
vii. power train 1 delivers power simultaneously to load and to power train2
viii. power train 1 delivers power to power train 2 and power train 2 delivers power aton load
ix. power train 1 delivers power to load and load delivers power to power train 2.

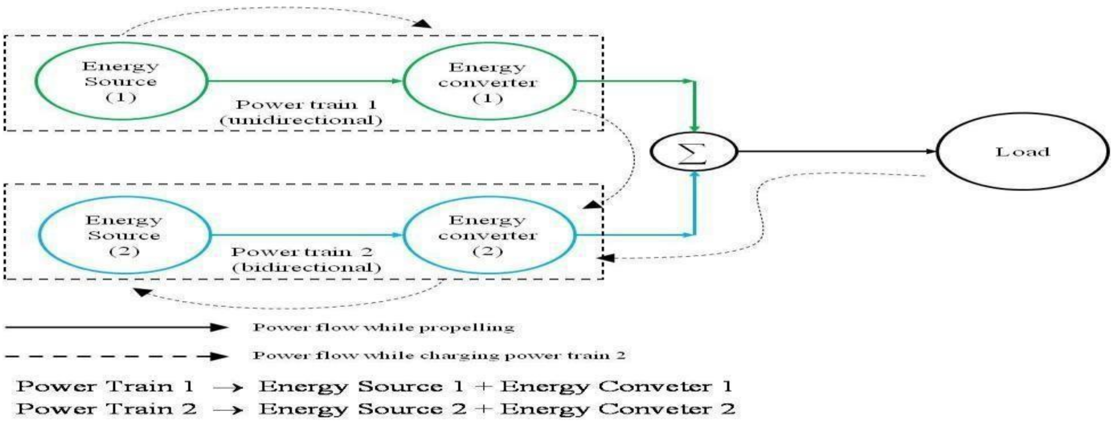


Figure 2: Generic Hybrid Drivetrain [1]

The load power of a vehicle varies randomly in actual operation due to frequent acceleration, deceleration and climbing up and down the grades. The power requirement for a typical driving scenario is shown in Figure 3. The load power can be decomposed into two parts:

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

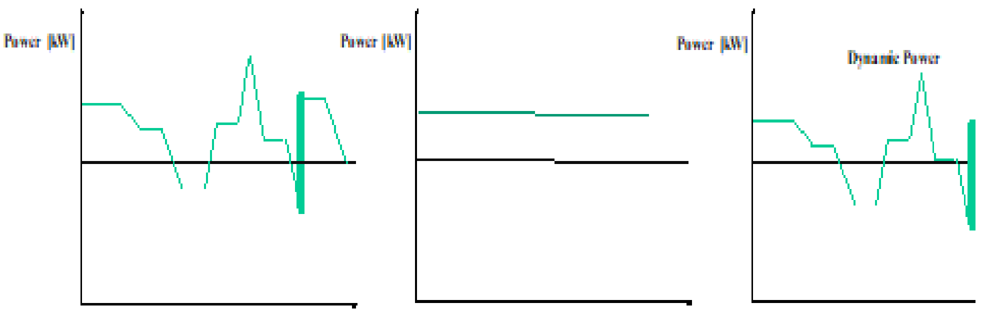


Figure3: Load power decomposition

In HEV one powertrain favors steady state operation, such as an ICE or fuel cell. The other powertrain in the HEV is used to supply the dynamic power. The total energy output from the dynamic powertrain will be zero in the whole driving cycle. Generally, electric motors are used to meet the dynamic power demand. This hybrid drivetrain concept can be implemented by different configurations as follows:

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

In **Figure 4** the functional block diagrams of the various HEV configurations is shown. From **Figure 4** it can be observed that the key feature of:

- series hybrid is to couple the ICE with the generator to produce electricity for pure electric propulsion.
- parallel hybrid is to couple both the ICE and electric motor with the transmission via the same drive shaft to propel the vehicle

Series Hybrid System:

In case of series hybrid system (**Figure 4a**) the mechanical output is first converted into electricity using a generator. The converted electricity either charges the battery or can bypass the battery to propel the wheels via the motor and mechanical transmission. 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 overallefficiency.
- Two electric machines are needed and a big traction motor is required because it is the only torque source of the drivenwheels.

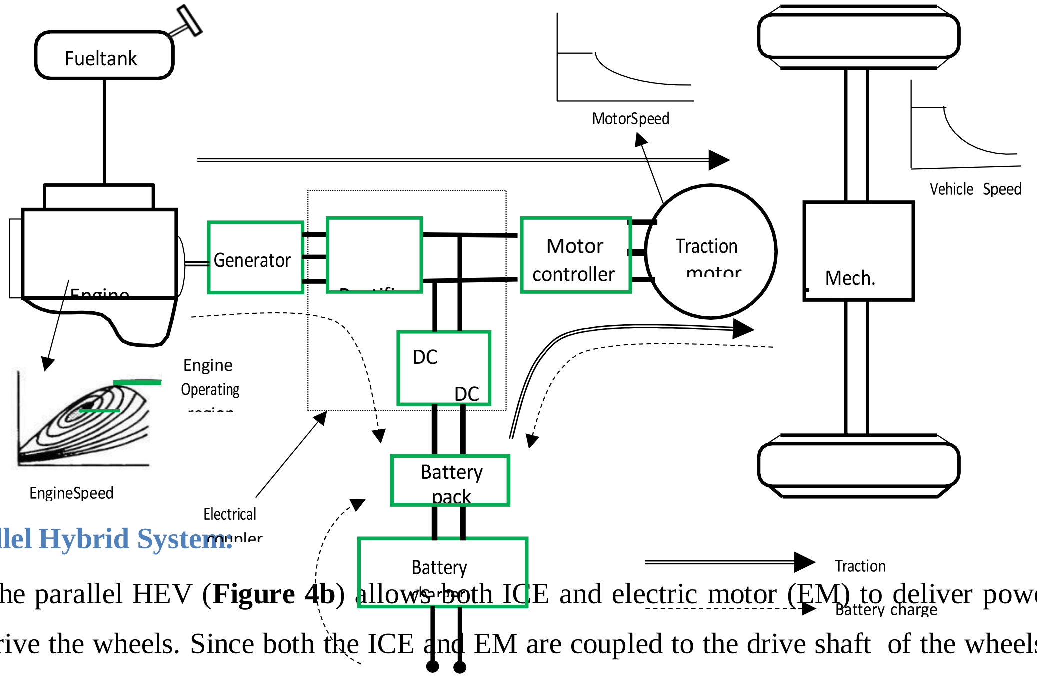
The series hybrid drivetrain is used in heavy commercial vehicles, military vehicles and buses. The reason is that large vehicles have enough space for the bulky engine/generator system.

Power

Torque

Tractive effort

Figure 5: Detailed Configuration of Series Hybrid Vehicle



Parallel Hybrid System:

The parallel HEV (**Figure 4b**) 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 EM can be used as a generator to charge the battery by regenerative braking or absorbing power from the ICE when its output is greater than that required to drive the wheels. The advantages of the parallel hybrid drive train are:

- both engine and electric motor directly supply torques to the driven wheels and no energy form conversion occurs, hence energy loss isless
- Compactness due to no need of the generator and smaller traction motor. The

drawbacks of parallel hybrid drive trains 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 drivetrain.

Due to its compact characteristics, small vehicles use parallel configuration. Most passenger cars employ this configuration.

Series-Parallel System:

In the series-parallel hybrid (**Figure 4c**), 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 (**Figure 4d**) 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.

POWER FLOW CONTROL:

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 satisfy the following goals:

- maximum fuelefficiency
- minimumemissions
- minimum systemcosts
- good drivingperformance

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 operatingline.
- ***Safe battery voltage:*** The battery voltage may be significantly altered during discharging, generator charging or regenerative charging. This battery voltage should not exceed the maximum voltage limit nor should it fall below the minimum voltage limit.

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 proper level.
- **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.

Mode 4: The battery can also be charged by the ICE via the generator even when the vehicle omes to a complete stop (**Figure)**

ELECTRIC DRIVE TRAINS:

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, distributed subsystems in the EV are really achievable.
- The EVs allow different propulsion arrangements such as independent four wheels and

in wheel drives.

In **Figure 1** 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

The energy source subsystem consists of

- The energy source (battery, fuel cell, ultracapacitor)
- Energy management unit
- Energy refueling unit

The auxiliary subsystem consists of

- Power steering unit
- Temperature control unit
- Auxiliary power supply

In **Figure 1** the black line represents the mechanical link, the green line represents the electrical link and the blue line represents the control information communication. Based on the control inputs from the brake and accelerator pedals, the electronic controller provides proper control signals to switch on or off the power converter which in turn regulates the power flow between the electric motor and the energy source. The backward power flow is due to regenerative braking of the EV and this regenerative energy can be stored provided the energy source is receptive.

The energy management unit cooperates with the electronic controller to control regenerative braking and its energy recovery. It also works with the energy-refueling unit to control refueling and to monitor usability of the energy source.

The auxiliary power supply provides the necessary power with different voltage levels for all EV auxiliaries, especially the temperature control and power steering units.

Electric propulsion subsystem

ELECTRIC TRAINS

ELECTRICAL MACHINES IN EVS AND HEVS:

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. The power rating mentioned in the catalog and on the name plate of the motor corresponds to the maximum power that the drive can deliver. Two most commonly used motors in EV propulsion are Permanent Magnet (PM) Motors and Induction Motors (IM). These two motors will be investigated in detail in the coming lectures. However, before going into the details of these machines some basic fundamentals of electrical machines, such as torque production, are discussed in this chapter.

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.

principle of operation:

The operation principle of a DC motor is straightforward. When a wire carrying electric current is placed in a magnetic field, a magnetic force acting on the wire is produced. The force is perpendicular to the wire and the magnetic field as shown in Figure 6.3. The magnetic force is proportional to the wire length, magnitude of the electric current, and the density of the magnetic field, that is,

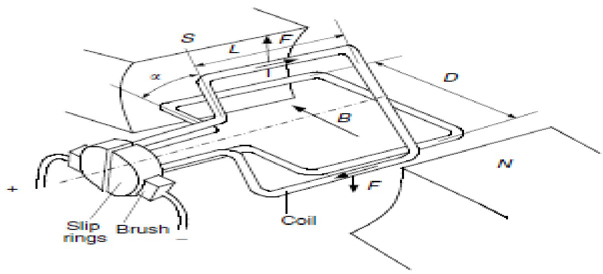
$$F = BIL.$$ ……................eq1

When the wire is shaped into a coil, as shown in Figure 6.3, the magnetic forces acting on both sides produce a torque, which is expressed as

$$T = BIL \cos \alpha,$$

…....................eq2

Figure 3.1: Operation principle of a DC motor



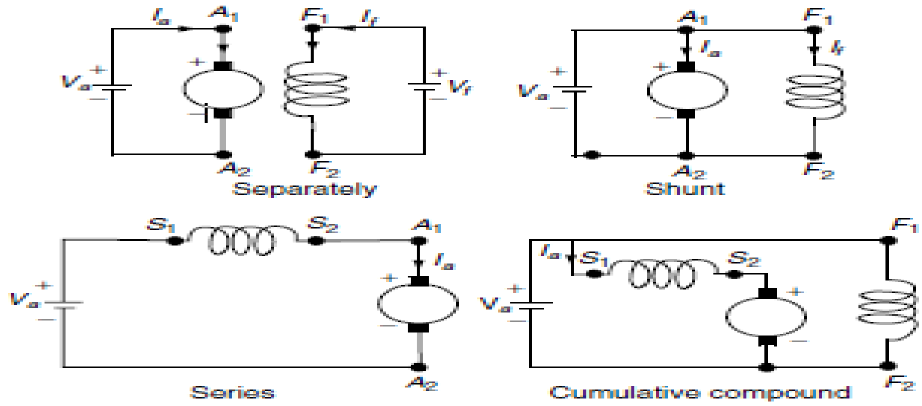
Where α is the angle between the coil plane and magnetic field as shown in Figure 3.1. The magnetic field may be produced by a set of windings or permanent magnets. The former is called wound-field DC motor and the latteris called the PM DC motor.

The coil carrying the electric current is called thearmature. In practice, the armature consists of a number of coils. In order to obtain continuous and maximum torque, slip rings and brushes are used toconduct each coil at the position of α=0.

Practically, the performance of DC motors can be described by the armaturevoltage, back electromotive force (EMF), and field flux.Typically, there are four types of wound-field DC motors, depending onthe mutual interconnection between the field and armature windings. Theyare separately excited, shunt excited, series excited, and compound excitedas shown in Figure 3.2.

In the case of a separately excited motor, the field and armature voltage can be controlled independently of one another.

In a shunt motor, the field and armature are connected in parallel to a common source. Therefore, an independent control of field current and armature or armature voltage can be achieved by inserting a resistance into the appropriate circuit.
This is an inefficient method of control. The efficient method is to use power electronics-based DC– DC converters in the appropriate circuit to replace the resistance.
The DC–DC converters can be actively controlled to produce proper armature and field voltage. In the case of a series motor, the field current is the same as the armature current; therefore, field flux is a function of armature current.
In a cumulative compound motor, the magnetomotive force (mmf) of a series field is a function of the armature current and is in thesame direction as the mmf of the shunt field.



The steady-state equivalent circuit of the armature of a DC motor is shown in Figure 3.3. The resistor *Ra* is the resistance of the armature circuit. For separatelyexcited and shunt DC motors, it is equal to the resistance of the armaturewindings; for the series and compound motors, it is the sum of armatureand series field winding resistances.

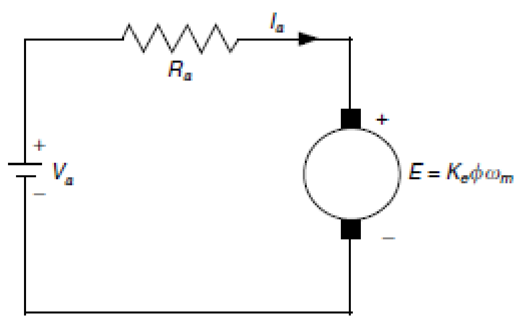


Figure 3.3: Steady-state equivalent circuit of the armature circuit of a DC motor

$$V_a = E + R_a I_a,\ E = K_e\phi\omega_m,$$

$$T = K_e\phi I_a, \qquad \text{……..... eq3}$$

Where φ is the flux per pole in Webers, *Ia*is the armature current in *A*, *Va* is the armature voltage in volt, *Ra* is the resistance of the armature circuit in ohms, ω*m*is the speed of the armature in rad/sec, *T* is the torque developed by the motor in Nm, and *Ke*is constant.
From equations 3 one can obtain

$$T = \frac{K_e\phi}{R_a}V - \frac{(K_e\phi)^2}{R_a}\omega_m. \qquad \text{…................... eq4}$$

Equations 3 are applicable to all the DC motors, namely, separately (or shunt) excited, series, and compound motors. In the case of separately excited motors, if the field voltage is maintained as constant, one can assume the flux to be practically constant as the torque changes. In this case, the speed–torque characteristic of a separately excited motor is a straight line, as shown in Figure 3.4.

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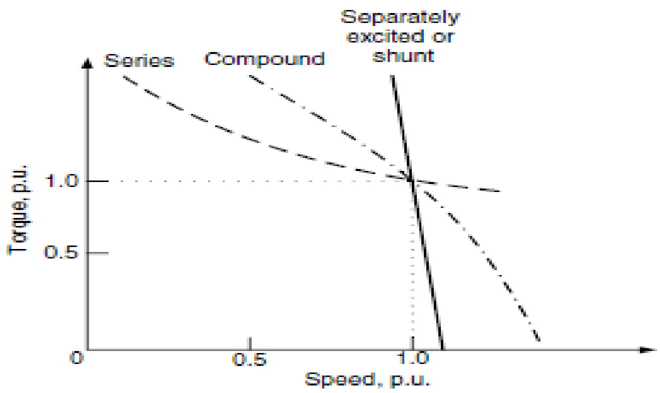
Figure 3.4 Speed characteristics of DC motors



The no load speed ω*m*0 is determined by the values of the armature voltage and the field excitation. Speed decreases as torque increases, and speed regulation depends on the armature circuit resistance. Separately excited motors are used in applications requiring good speed regulation and proper adjustable speed.
In the case of series motors, the flux is a function of armature current. Inan unsaturated region of the magnetization characteristic, φ can be assumed to be proportional to *Ia*. Thus

$$\phi = K_f I_a, \quad \ldots \ldots\ldots\ldots\ldots eq5$$

By equations 3&5, the torque for series excited DC motors can obtained as

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

A speed–torque characteristic of a series DC motor is shown in Figure 3.4.In the case of series, any

in magnetic flux. Because flux increases with the torque, the speed drops to maintain a balance between the induced voltage and the supply voltage. The characteristic, therefore, shows a dramatic drop. A motor of standard design works at the knee point of the magnetization curve at the rated torque. At heavy torque (large current) overload, the magnetic circuit saturates and the speed–torque curve approaches a straight line.
Series DC motors are suitable for applications requiring high starting torqueand heavy torque overload, such as traction. This was just the case for electrictraction before the power electronics and micro control era. However, series DC motors for traction application have some disadvantages. They are notallowed to operate without load torque with full supply voltage. Otherwise,
their speed will quickly increase up to a very high value . Another disadvantage is the difficulty in regenerative braking. Performance equations for cumulative compound DC motors can be
derived from equations (3).

The speed–torque characteristics arebetween series and separately excited (shunt) motors, as shown in Figure 3.4.

COMBINED ARMATURE VOLTAGE AND FIELD CONTROL

The independence of armature voltage and field provides more flexible control of the speed and torque than other types of DC motors. In EV and HEVapplications, the most desirable speed–torque characteristic is to have a constant torque below a certain speed (base speed), with the torque dropping parabolically with the increase of speed (constant power) in the range abovethe base speed, as shown in Figure 6.7. In the range of lower than base speed, the armature current and field are set at their rated values, producing the rated torque. From equations (3), it is clear that the armature voltage must be increased proportionally with the increase of the speed. At thebase speed, the armature voltage reaches its rated value (equal to the source voltage) and cannot be increased further. In order to further increase thespeed, the field must be weakened with the increase of the speed, and then the back EMF E and armature current must be maintained constant. The torque produced drops parabolically with the increase in the speed and the output power remains constant, as shown in Figure 3.5.

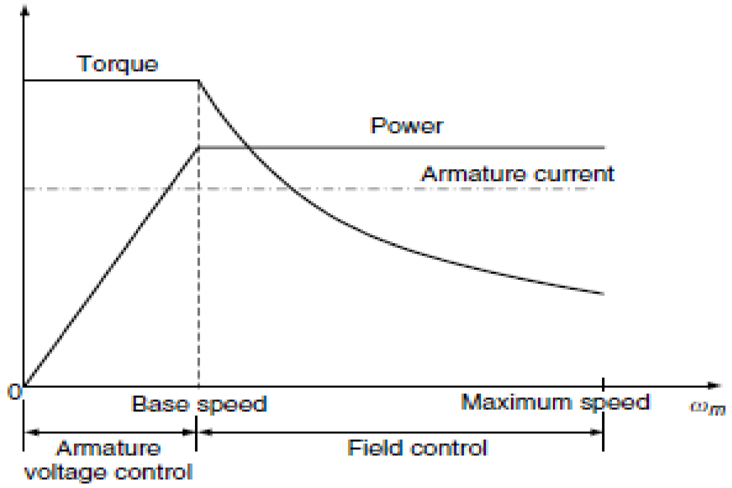


Figure3.5: Torque and power limitations in combined armature voltage and field control

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. High operation frequency results in high-frequency output voltage ripple and, therefore, less ripples in the motor armature current and a smaller region of discontinuous conduction in the speed–torque plane. A reduction in the armature current ripple reduces the armature losses. A reduction or elimination of the discontinuous conduction region improves speed regulation and the transient response of the drive.

The power electronic circuit and the steady-state waveform of a DC chopper drive are shown in Figure 3.6

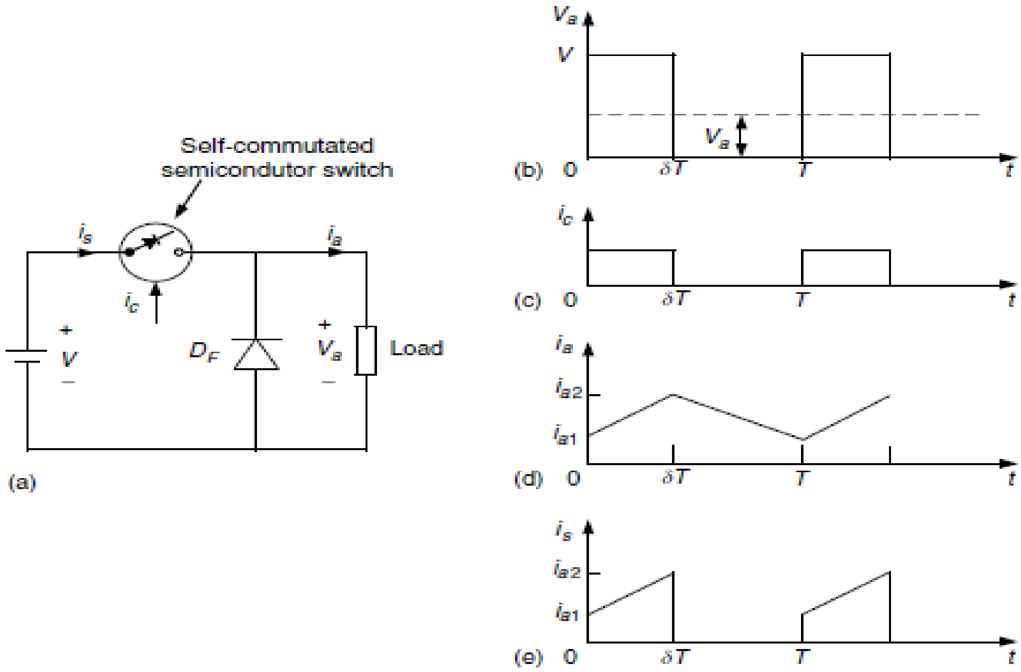


Figure3.6: Principle of operation of a step down (or class A) chopper: (a) basic chopper circuit; (b) to (e)waveforms

ADC 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$t_{on}=\delta T$with $0\le\delta\le1$. The variable$\delta=t_{on}/T$ 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 or the main thyristor of a thyristor chopper. If a power MOSFET isused, it will be a gate to the source voltage. When the control signal is present, the semiconductor switch *S* will conduct, if forward biased. It is assumed that the circuit operation has been arranged such that the removalof*ic*will turn off the switch.

During the on interval of the switch ($0\le t\le\delta T$), the load is subjected to a voltage*V*and the load current increases from i_{a1} to i_{a2}. The switch is opened at$t=\delta T$. During the off period of the switch ($\delta T\le t\le1$), the load inductance maintains the flow of current through diode *DF*. The load terminal voltage remains zero (if the voltage drop on the diode is ignored in comparison to *V*)and the current decreases from i_{a2} to i_{a1}. The internal $0\le t\le\delta T$ is called the duty interval and the interval $\delta T\le t\le T$ is known as the freewheeling interval.

Diode *DF* provides a path for the load current to flow when switch *S* isoff, and thus improves the load current waveform. Furthermore, by maintaining the continuity of the load current at turn off, it prevents transient voltage from appearing across switch *S*, due to the sudden change of the load current.

The source current waveform is also shown in Figure 6.8e. The source current flows only during the duty interval and is equal to the load current. The direct component or average value of the load voltage *Va* is given by

$$\bar{V}_a=\frac{1}{T}\int_0^T v_a\,dt=\frac{1}{T}\int_0^{\delta T}V\,dt=\delta t. \qquad \text{…......... eq7}$$

By controlling δ between 0 and 1, the load voltage can be varied from 0 to *V*;thus, 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 ratioδ.

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:

1. Constant frequency TRC:
2. The chopper period *T* is kept fixed and

the on period of the switch is varied to control the duty ratio δ.

3. Varied frequency TRC:
4. Here, δ is varied either by keeping *ton* constantand varying *T* or by varying both *ton* and *T*. In variable frequency control with constant on-time, low-output voltage is obtained at very low values of chopper frequencies. The operation of a chopper at low frequencies adversely affects the motor performance. Furthermore, the operation of a chopper with variable frequencies makes the design of an input filter very difficult. Thus, variable frequency control israrely used.

In current limit control, also known as point-by-point control, δ is controlled indirectly by controlling the load current between certain specified maximum and minimum values. When the load current reaches a specified maximum value, the switch disconnects the load from the source and reconnectsItwhen the current reaches a specified minimum value. For a DC motor load, this type of control is, in effect, a variable frequency variable on time control.

The following important points can be noted from the waveform ofFigure3.5:

1. The source current is not continuous but flows in pulses. The pulsed current makes the peak input power demand high and may cause fluctuation in the source voltage. The source current waveform can be resolved into DC and AC harmonics. The fundamental AC harmonic frequency is the same as the chopper frequency. The AC harmonics are undesirable because they interfere with other loads connected to the DC source and cause radio frequency interference through conduction and electromagnetic radiation. Therefore, anL-C filter is usually incorporated between the chopper and the DC source. At higher chopper frequencies, harmonics can be reduced toa tolerable level by a cheaper filter. From this point, a chopper should be operated at the highest possible frequency.
2. The load terminal voltage is not a perfect direct voltage. In addition to a direct component, it has harmonics of the chopping frequency and its multiples. The load current also has an AC ripple.

The chopper of Figure 3.6 is called a class A chopper. It is one of a numberof chopper circuits that are used for the control of DC motors. This chopperis capable of providing only a positive voltage and a positive current. It istherefore called a single-quadrant chopper, capable of providing DCseparatelyexcited motor control in the first quadrant, positive speed, and positivetorque. Since it can vary the output voltage from *V* to 0, it is also a step-downchopper or a DC to DC buck converter. The basic principle involved can alsobe used to realize a step-up chopper or DC to DCboostconverter. The circuit diagram and steady-state waveforms of a step-up chopper areshown in Figure 3.6. This chopper is known as a class B chopper. The presence of control signal *ic*indicates the duration for which the switch can conduct

if forward-biased. During a chopping period *T*, it remains closed for aninterval $0 \le t \le \delta T$ and remains open for an interval $\delta T \le t \le T$. During the on period, *iS*increases from *iS*1 to *iS*2, thus increasing the magnitude of energystored in inductance *L*. When the switch is opened, current flows through the parallel combination of the load and capacitor *C*. Since the current isforced against the higher voltage,the rate of change of the current is negative. It decreases from *iS*2 to *iS*1 in the switch's off period. The energy storedin the inductance *L* and the energy supplied by the low-voltage source aregiven to the load. The capacitor *C* serves two purposes. At the instant ofopening of switch *S*, the source current, *iS*, and load current, *ia*, are not the same. In the absence of *C*, the turn off of *S* will force the two currents to have the same values. This will cause high induced voltage in the inductance *L*and the load inductance. Another reason for using capacitor *C* is to reduce the load voltage ripple. The purpose of the diode *D* is to prevent any flow ofcurrent from the load into switch *S* or source *V*.

For understanding the step-up operation, capacitor *C* is assumed to be large enough to maintain a constant voltage *Va* across the load. The averagevoltage across the terminal *a*, *b* is given as

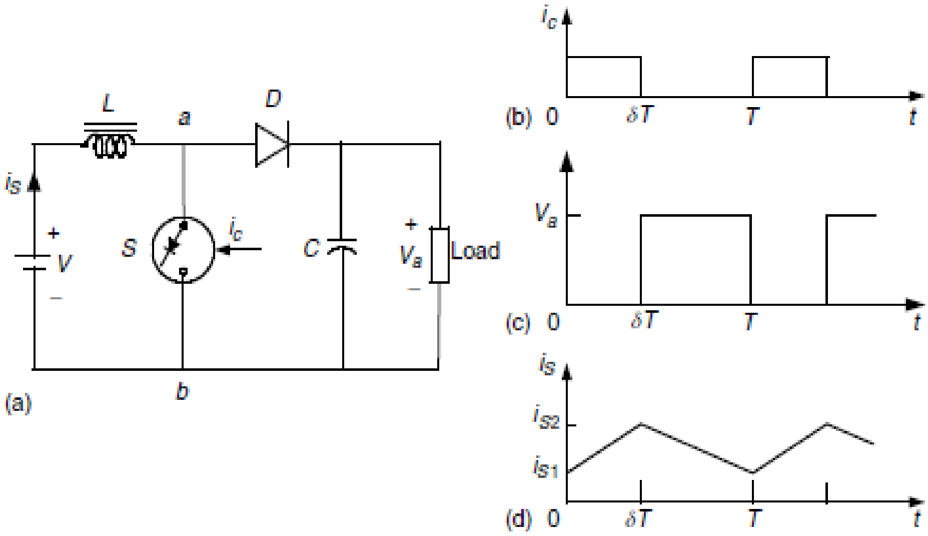


Figure3.7: Principle of operation of a step-up (or class B) chopper: (a) basic chopper circuit; (b) to (d)waveforms

$$V_{ab} = \frac{1}{T}\int_0^T v_{ab}\,dt = V_a(1-\delta$$ ……………..eq8

The average voltage across the inductance *L* is

$$V_L = \frac{1}{T}\int_0^T\left(L\frac{di}{dt}\right)dt = \frac{1}{T}\int_{i_{s1}}^{i_{s2}} L\,di = 0.$$ …………………eq9

The source voltage is

$$V = V_L + V_{ab}.$$ …....................... eq10

Substituting from equations (8) and (9) into (10) gives

$$V = V_a(1-\delta)\text{ or } V_a = \frac{V}{1-\delta}$$ …………..eq11

According to (11), theoretically the output voltage *Va* can be changed from*V*to∞ by controlling δ from 0 to 1. In practice, *Va* can be controlled from *V* to a higher voltage, which depends on the capacitor *C*, and the parametersof the load and chopper.

The main advantage of a step-up chopper is the low ripple in the source current. While most applications require a step-down chopper, the step-up chopper finds application in low-power battery-driven vehicles. The principle of the step-up chopper is also used in the regenerative braking ofDC motor drives.

UNIT-IV

BATTERY TECHNOLOGIES:

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.3 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.

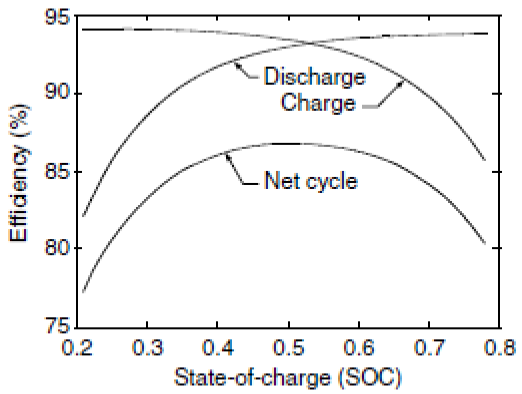


FIGURE 4.10Typical battery charge and discharge efficiency

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 advantagesare attractive for its application in HEVs where high power is the firstconsideration. 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 batteriesmay 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.

Different lead-acid batteries with improved performance are beingdeveloped 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 isElectro source's Horizon battery. It adopts the lead wire woven horizontalplate and hence offers long cycle life (over 600 cycles for on-road EV application), rapid recharge capability (50% capacity in 8 minand 100% in less than 30 min), low cost (US$2000–3000 an EV), mechanicalruggedness (robust structure of horizontal plate), maintenance-free conditions(sealedbatterytechnology), and environmental friendliness. Otheradvanced lead-acid batterytechnologies include bipolar designs and microtubular griddesigns. Advanced lead-acid batteries have been developed to remedy these disadvantages. The specific energy has been increased through the reductionof inactive materials such as the casing, current collector, separators, etc. The lifetime has been increased by over 50% — at the expense of cost, however. The safety issue has been addressed and improved, with electrochemical processes designed to absorb the parasitic releases ofhydrogen and oxygen.

NICKEL-BASED BATTERIES:

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

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.1 The system comprises a nickel (III) hydroxy-oxide (NiO OH) 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 4.6 and its nominal open-circuit voltage is1.37v

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NICKEL/CADMIUM SYSTEM:

The nickel/cadmium system uses the same positive electrodes and electrolyteas the nickel/iron system, in combination with metallic cadmiumnegative 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 hascoincided with that ofnickel/iron and they have a similar performance. Nickel/cadmium technology has seen enormous technical improvementbecause of the advantages of high specific power (over 220 W/kg), longcycle 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-termstorage due to negligible corrosion, and availability in a variety of sizedesigns. However, the nickel/cadmium battery has some disadvantages, including high initial cost, relatively low cell voltage, and the carcinogenicityand environmental hazard of cadmium. Nickel/iron batteries suffer from gassing, corrosion, and self-discharge problems. These problems

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 mechanicalabuse, a small voltage drop over a wide range of discharge currents, rapidcharge 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-termstorage due to negligible corrosion, and availability in a variety of size designs. However, the nickel/cadmium battery has some disadvantages, including high initial cost, relatively low cell voltage, and the carcinogenicity and environmental hazard of cadmium.

The nickel/cadmium battery can be generally divided into two major categories, namely the vented and sealed types. The vented type consists of many alternatives. The vented sintered-plate is a more recent development, which has a high specific energy but is more expensive. It is characterized by a flat discharge voltage profile, and superior high current rate and low-temperature performance. A sealed nickel/cadmium battery incorporates a specific cell design feature to prevent a build-up of pressure in the cell caused by gassing during overcharge. As a result, the battery requires no maintenance.

The major manufacturers of the nickel/cadmium battery for EV and HEVallocation are SAFT and VARTA. Recent EVs powered by the nickel/cadmium battery have included the Chrysler TE Van, Citroën AX, Mazda Roadster, Mitsubishi EV, Peugeot 106, and Renault Clio.3,6

NICKEL–METAL HYDRIDE (NI–MH) BATTERY

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 from toxicity or carcinogenicity, the Ni–MH battery is superseding the Ni–Cd battery. The overall reaction in a Ni– MH battery is

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

… eq1

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. Akey component of the Ni–MH battery is the hydrogen storage metal alloy, which is formulated to obtain a material that is stable over a large number of cycles. There are two major types of these metal alloys being used. These are the rare- earth alloys based around lanthanum nickel, known as AB5, and alloys consisting of titanium and zirconium, known as AB2. The AB2 alloys have a higher capacity than the AB5 alloys. However, the trend is to use AB5alloys because of better charge retention and stability characteristics. Since the Ni–MH battery is still under development, its advantages based on present technology are summarized as follows: it has the highest specific energy (70 to 95 Wh/kg) and highest specific power (200 to 300 W/kg) of nickel-based batteries, environmental friendliness (cadmium free), a flat discharge profile (smaller voltage drop), and rapid recharge capability. However, this battery stil suffers from its high initial cost. Also, it may havea memory effect and may be exothermic on charge.

The Ni–MH battery has been considered as an important near-term choice for EV and HEV applications. A number of battery manufacturers, such asGM Ovonic, GP, GS, Panasonic, SAFT, VARTA, and YUASA, have activelyengaged in the development of this battery technology, especially for poweringEVs and HEVs. Since1993, Ovonic battery has installed its Ni–MH batteryin the Solectron GT Force EV for testing and demonstration. A 19-kWhbattery has delivered over 65 Wh kg, 134 km/h, acceleration from zero to 80km/h in 14 sec, and a city driving range of 206 km. Toyota and Honda haveused the Ni–MH battery in their HEVs — Prius and Insight, respectively.

LITHIUM-BASED BATTERIES

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

LITHIUM–POLYMER (LI–P) BATTERY:

Lithium–polymer batteries use lithium metal and a transition metal intercalation oxide (M*y*O*z*) for the negative and positive electrodes, respectively. This M*y*O*z* possesses a layered structure into which lithium ions can be inserted, or from where they can be removed on discharge and charge, respectively. A thin solid polymer electrolyte (SPE) is used, which offers themerits of improved safety and flexibility in design. The general electrochemical reactions are

$$x\mathrm{Li}+\mathrm{M}_y\mathrm{O}_z \leftrightarrow \mathrm{Li}_x\mathrm{M}_y\mathrm{O}_z. \quad \text{………. eq2}$$

On discharge, lithium ions formed at the negative electrode migrate through the SPE, and are inserted into the crystal structure at the positive electrode. On charge, the process is reversed. By using a lithium foil negative electrode and vanadium oxide (V6O13) positive electrode, the Li/SPE/V6O13 cell is the most attractive one within the family of Li–polymer. It operates at a nominal voltage of 3 V and has a specific energy of 155 Wh/kg and a specific power of 315 W/kg. The corresponding advantages are a very low self-discharge rate (about 0.5% per month), capability of fabrication in a variety of shapes and sizes, and safe design (reduced activity of lithium with solid electrolyte). However, it has the drawback of a relatively weak low-temperature performance due to the temperature dependence of ionic conductivity.

LITHIUM-ION (LI-ION) BATTERY:

Since the first announcement of the Li-ion battery in 1991, Li-ion battery technology has seenanunprecedented rise to what is now considered to bethe most promising rechargeable battery of thefuture. Although still atthedevelopment stage, the Li-ion battery has already gained acceptance for EVand HEV applications.

The Li-ion battery uses a lithiated carbon intercalation material (Li*x*C) forthe negative electrode instead of metallic lithium, a lithiated transitionmetal intercalation oxide (Li1_*x* M*y*O*z*) for the positive electrode, and a liquidorganic solution or a solid polymer for the electrolyte. Lithium ions swing through the electrolyte between the positive and negative electrodesduring discharge and charge. The general electrochemical reaction is described as

$$\mathrm{Li}_x\mathrm{C}+\mathrm{Li}_{1-x}\mathrm{M}_y\mathrm{O}_z \leftrightarrow \mathrm{C}+\mathrm{Li}\mathrm{M}_y\mathrm{O}_z. \quad \text{……. eq3}$$

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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 onthe SOC, it is difficult to use ultracapacitors alone as an energy storage forEVs 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 specificpower requirements can be decoupled, thus affording an opportunity todesign a battery that is optimized for the specific energy and cycle life withlittle attention being paid to the specific power. Due to the load levelling effect of the ultracapacitor, the high-current discharging from the batteryand the high-current charging to the battery by regenerative braking is minimized so that the available energy, endurance, and life of the battery can besignificantly increased.

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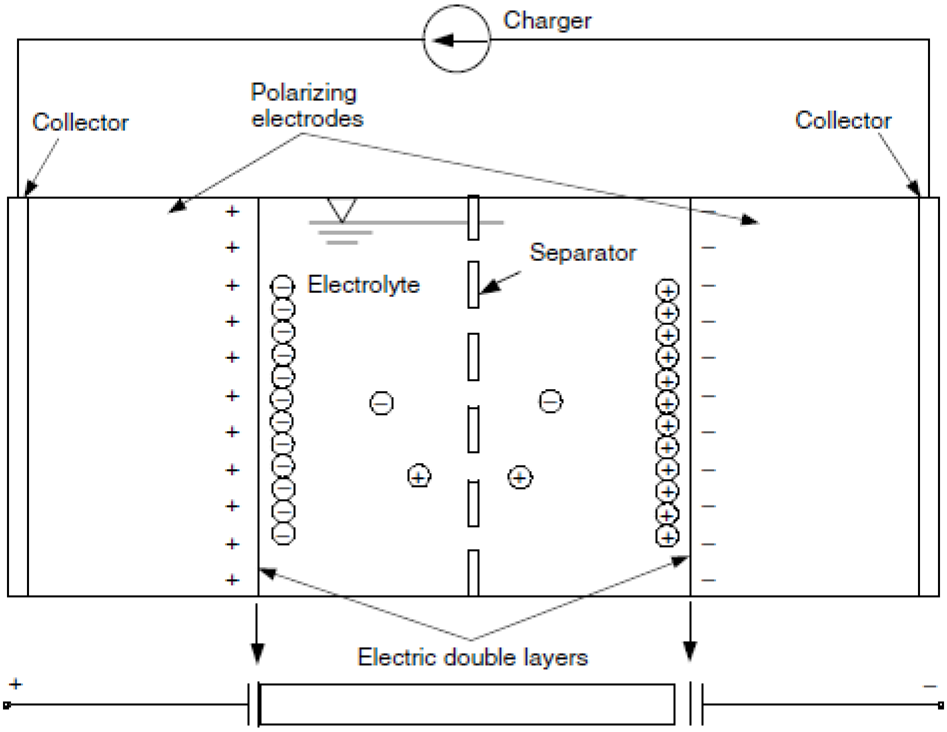


FIGURE 4.11: Basic principles of a typical electric double-layer capacitor

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

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

…............eq4

where *C* is the capacitance in Faraday and *V* is the usable voltage in volt.This equation indicates that the higher rated voltage *V* is desirable for larger energy density capacitors. Up to now, capacitors' rated voltage with an aqueous electrolyte has been about 0.9 V per cell, and 2.3 to 3.3 V for each cell with a nonaqueous electrolyte. There is great merit in using an electric double layer in place of plastic oraluminium 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 aremade 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 electrolyteis added, 25 F/g is quite a large capacity density. Nevertheless, theenergy 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.

PERFORMANCE OF ULTRACAPACITORS:

The performance of an ultracapacitor may be represented by terminal voltages during discharge and charge with different current rates. There arethree parameters in a capacitor: the capacitance itself (its electric potential*VC*), the series resistance *RS*, and the dielectric leakage resistance, *RL*, asshown in Figure 4.12. The terminal voltage of the ultracapacitor during dischargecan be expressed as

$$V_t = V_C - iR_S.$$

…............. eq5

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

…………eq6

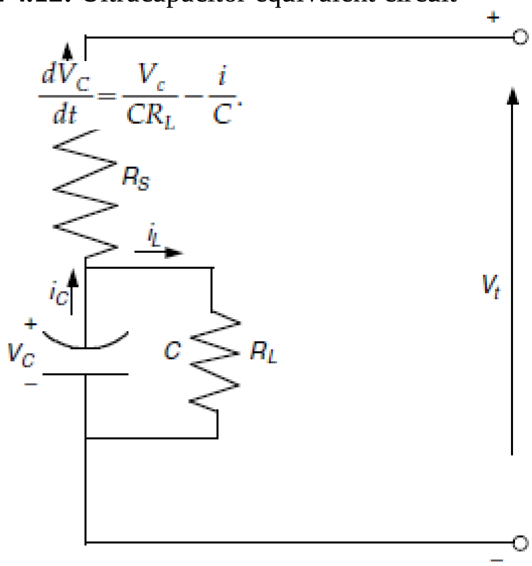
where C is the capacitance of the ultracapacitor. On the other hand, the leakagecurrent iLcan be expressed as

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

…......... eq7

FIGURE 4.12: Ultracapacitor equivalent circuit

$$\frac{dV_C}{dt} = \frac{V_c}{CR_L} - \frac{i}{C}.$$



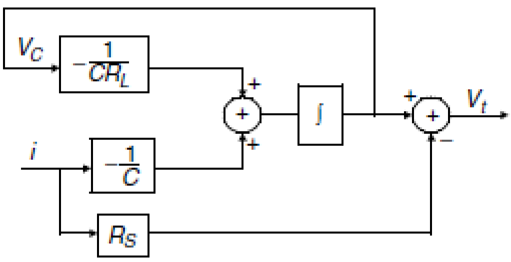
The terminal voltage of the ultracapacitor cell can be represented by the diagramas shown in Figure

10.10. The analytical solution of (eq8) is

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

where i is the discharge current, which is a function of time in real operation. The discharge characteristics of the Maxwell 2600 F ultracapacitor are shown in Figure 4.14. At different discharge current rates, the voltage decreases linearlywith discharge time. At a large discharge current rate, the voltage decreases much faster than at a small current rate.

FIGURE 4.13: Block diagram of the ultracapacitor model



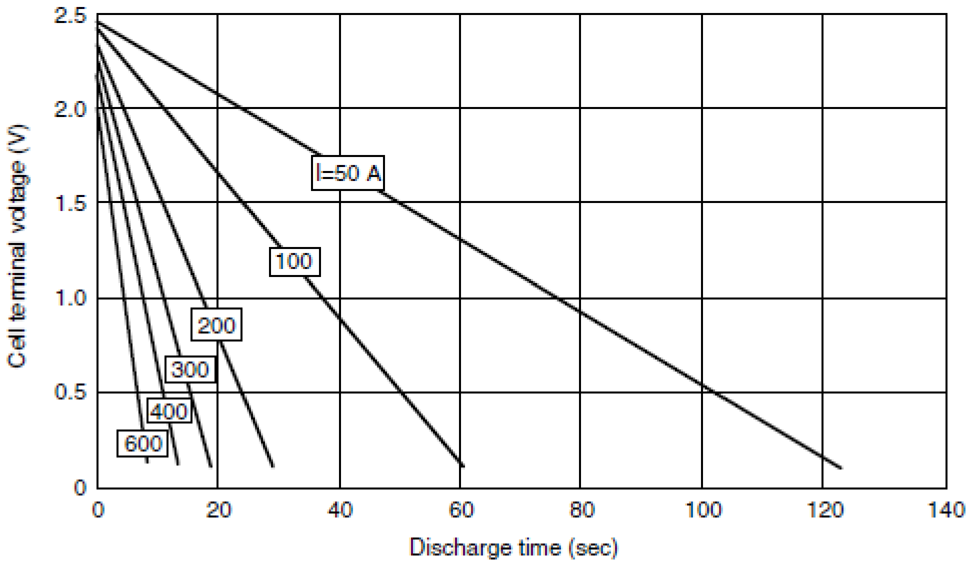


FIGURE 4.14: Discharge characteristics of the 2600 F Maxwell Technologies ultracapacitor

A similar model can be used to describe the charging characteristics of anultracapacitor, and readers who are interested may do their own analysisand simulation.

The operation efficiency in discharging and charging can be expressed as:

discharging:

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

and eq10

chargin
g:

$$\eta_c = \frac{V_C I_C}{V_t I_t} = \frac{V_C(I_t - I_L)}{(V_C + I_t R_s) I_t},$$ eq11

where *Vt* is the terminal voltage and *It* is the current input to or output fromthe terminal. In actual operation, the leakage current *IL* is usually very small(few mA) and can be ignored. Thus, equations
(10) and (11) can berewritten as:
discharging:

$$\eta_d = \frac{V_C - R_S I_t}{V_C} = \frac{V_t}{V_C}$$

And

charging:

$$\eta_c = \frac{V_C}{V_C + R_s I_t} = \frac{V_C}{V_t}.$$

.... eq13

The above equations indicate that the energy loss in an ultracapacitor iscaused by the presence of seriesresistance. The efficiency decreases at a highcurrent rate and low cell voltage, as shown in Figure 4.15. Thus, in actual

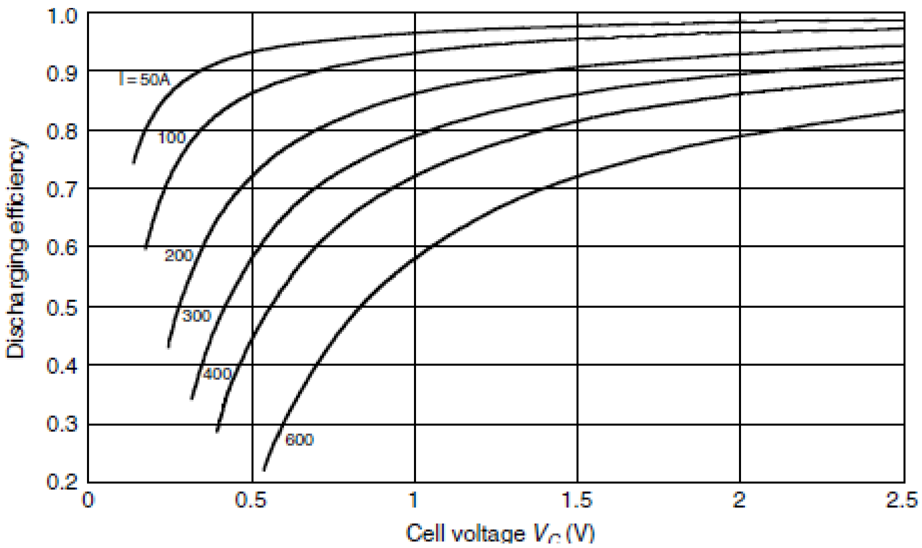


FIGURE 4.15: Discharge efficiency of the 2600 F Maxwell Technologies ultracapacitor operation, the ultracapacitor should be maintained at its high voltage region, for more than 60% of its rated voltage.
The energy stored in an ultracapacitor can be obtained through the energyneeded to charge it to a certain voltage level, that is,

$$E_C = \int_0^t V_C I_C \, dt = \int_0^V C V_C \, dV_C = \frac{1}{2} C V_C^2,$$ eq14

where *VC* is the cell voltage in volts. At its rated voltage, the energy stored in the ultracapacitor reaches its maxima. Equation (10.31) indicates that increasing the rated voltage can significantly increase the stored energy since the energy increases with the voltage squared. In real operation, itis impossible to utilize the stored energy completely because of the low power in the low SOC (low voltage). Thus, an ultracapacitor is usually given a bottom voltage, *VCb*, below which the ultracapacitor will stop delivering energy. Consequently, the available or useful energy for use is less than its fully charged energy, which can be expressed as

$$E_u = \frac{1}{2} C\left(V_{CR}^2 - V_{Cb}^2\right), \qquad \text{..................eq15}$$

where *VCR* is the rated voltage of the ultracapacitor. At its bottom voltage, theSOC can be written as

$$SOC = \frac{0.5\,CV_{Cb}^2}{0.5\,CV_{CR}^2} = \frac{V_{Cb}^2}{V_{CR}^2}.$$

. ... eq16

For example, when the cell voltage drops from rated voltage to 60% of therated voltage, 64% of the total energy is available for use, as shown inFigure 415.

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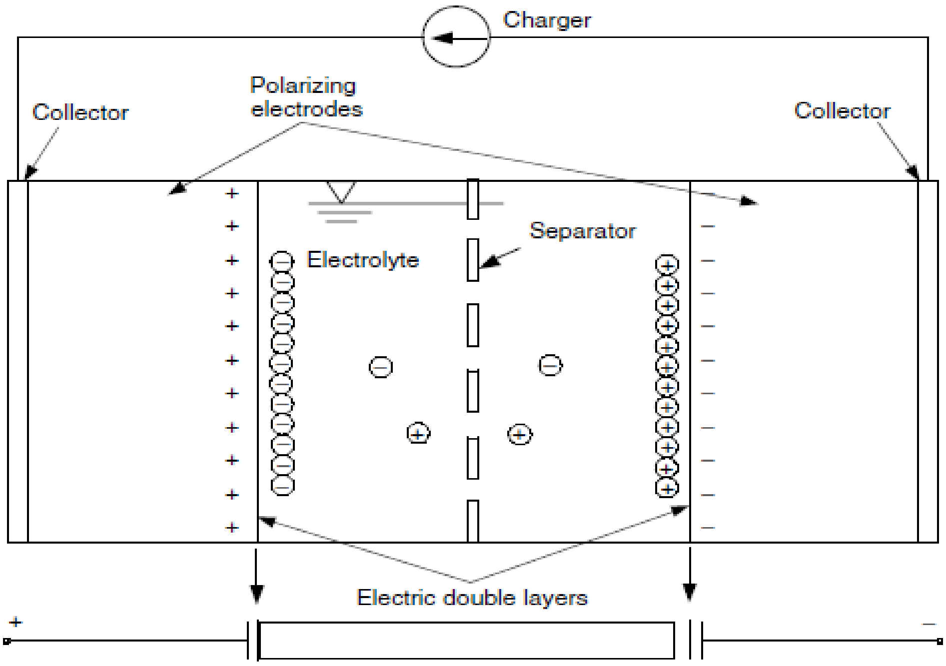

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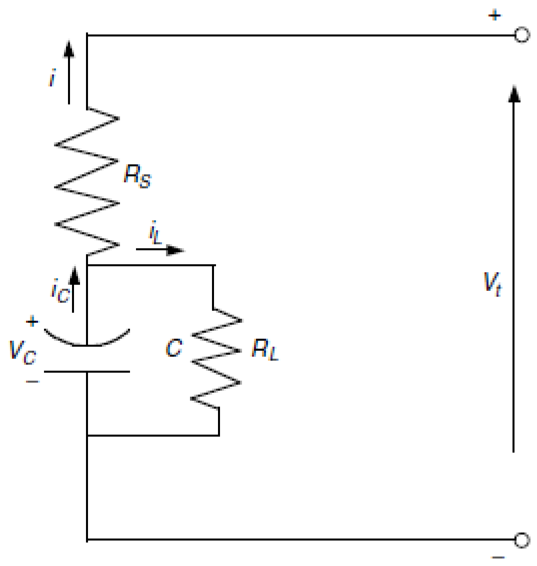

expressed as

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…......... eq7

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…...... eq9

where *i* is the discharge current, which is a function of time in real operation. The discharge characteristics of the Maxwell 2600 F ultracapacitor are shown in Figure 4.14. At different discharge current rates, the voltage decreases linearlywith discharge time. At a large discharge current rate, the voltage decreases much faster than at a small current rate.

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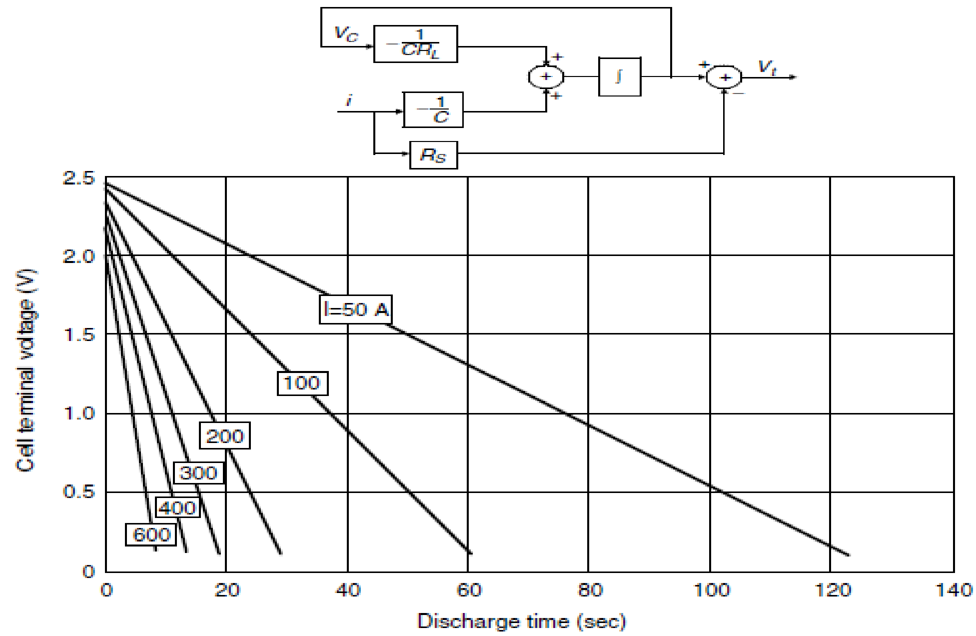

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.... eq1

charging and
:

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.

e
q
1
1

where *Vt* is the terminal voltage and *It* is the current input to or output fromthe terminal. In actual operation, the leakage current *IL* is usually very small(few mA) and can be ignored. Thus, equations
(10) and (11) can berewritten as:
discharging:

$$\eta_d = \frac{V_C - R_S I_t}{V_C} = \frac{V_t}{V_C}$$

.... eq12

And

charging:

$$\eta_c = \frac{V_C}{V_C + R_s I_t} = \frac{V_C}{V_t}.$$

..................eq13

The above equations indicate that the energy loss in an ultracapacitor iscaused by the presence of seriesresistance. The efficiency decreases at a highcurrent rate and low cell voltage, as shown in Figure 4.15. Thus, in actual

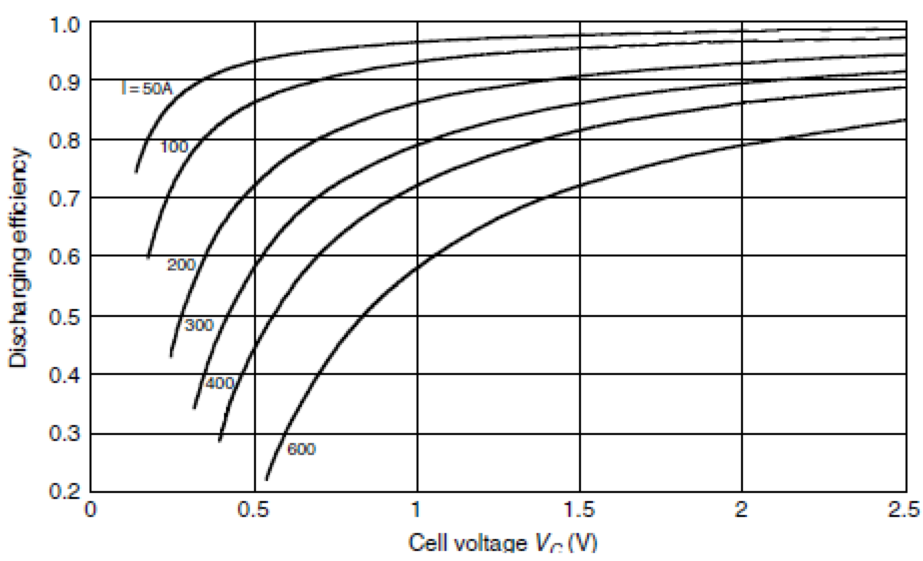


FIGURE 4.15: Discharge efficiency of the 2600 F Maxwell Technologies

ultracapacitor operation, the ultracapacitor should be maintained at its high voltage region, for more than 60% of its rated voltage.

The energy stored in an ultracapacitor can be obtained through the energyneeded to charge it to a certain voltage level, that is,

$$E_C = \int_0^t V_C I_C \, dt = \int_0^v C V_C \, dV_C = \frac{1}{2} C V_C^2,$$

………………. eq14

where *VC* is the cell voltage in volts. At its rated voltage, the energy stored in the ultracapacitor reaches its maxima. Equation (10.31) indicates that increasing the rated voltage can significantly increase the stored energy since the energy increases with the voltage squared. In real operation, itis impossible to utilize the stored energy completely because of the low power in the low SOC (low voltage). Thus, an ultracapacitor is usually given a bottom voltage, *VCb*, below which the ultracapacitor will stop delivering energy. Consequently, the available or useful energy for use is less than its fully charged energy, which can be expressed as

$$E_u = \frac{1}{2} C\left(V_{CR}^2 - V_{Cb}^2\right),$$

.... eq15

where *VCR* is the rated voltage of the ultracapacitor. At its bottom voltage, theSOC can be written as

$$SOC = \frac{0.5\, C V_{Cb}^2}{0.5\, C V_{CR}^2} = \frac{V_{Cb}^2}{V_{CR}^2}.$$

…....................eq16

For example, when the cell voltage drops from rated voltage to 60% of therated voltage, 64% of the total energy is available for use, as shown inFigure 415.

4.7.4. ULTRACAPACITOR TECHNOLOGIES:

According to the goals set by the U.S. Department of Energy for the inclusionof ultracapacitors in EVs and HEVs, the near-term specific energyand specific power should be better than 5 Wh/kg and 500 W/kg, respectively, while the advanced performance values should be over 15 Wh/kgand 1600 W/kg. So far, none of the available ultracapacitors can fully satisfy these goals. Nevertheless, some companies are actively engaged in the research and development of ultracapacitors for EV and EHV applications. Maxwell Technologies hasclaimed that its power BOOSTCAP ultracapacitor cells (2600 F at 2.5 V) and integrated modules (145 F at 42 Vand435 F at 14 V) are in production. The technical specifications are listedin Table 4.9.

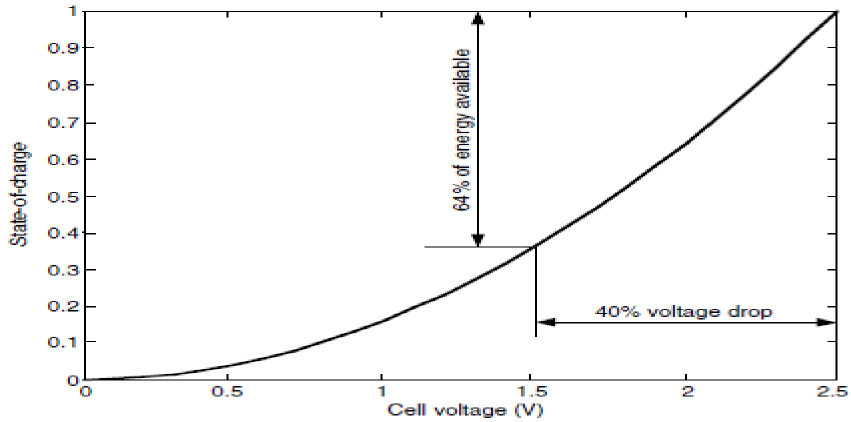


TABLE 4.9: Technical Specifications of the Maxwell Technologies Ultracapacitor Cell andIntegrated Modules5

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 inSwitzerland made the first passenger bus solely powered by a massive flywheel. This flywheel, which weighed 1500 kg and operated at 3000 rpm, wasrecharged 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

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

[a]Steady-state case temperature.

power, long cycle life, high-energy efficiency, quick recharge, maintenance free characteristics, costeffectiveness, and environmental

OPERATION PRINCIPLES OF FLYWHEELS:

A rotating flywheel stores energy in the kinetic form as

$$E_f = \frac{1}{2} J_f \omega_f^2,$$

......................eq1

where $J_f$is the moment of inertia of the flywheel in kgm2/sec and $\omega_f$is the angular velocity of the flywheel in rad/sec. Equation (10.32) indicates that enhancing the angular velocity of the flywheel is the key method of increasing its energy capacity and reducing its weight and volume. At present, a speed of over 60,000 rpm has been achieved in some prototypes. With current technology, it is difficult to directly use the mechanical energy stored in a flywheel to propel a vehicle, due to the need for continuous variation transmission (CVT) with a wide gear ratio variation range. The commonly used approach is to couple an electric machine to the flywheel directly or through a transmission to constitute a so-called mechanical battery. The electric machine, functioning as the energy input and output port, converts the mechanical energy into electric energy or vice versa, as shown in Figure 4.17. Equation (1) indicates that the energy stored in a flywheel is proportional to the moment of inertia of the flywheel and flywheel rotating speed squared. A lightweight flywheel should be designed to achieve moment of inertia per unit mass and per unit volume by properly designing its geometric shape.
The moment of inertia of a flywheel can be calculated by

$$J_f = 2\pi\rho\int_{R_1}^{R_2} W(r) r^3 \, dr,$$ eq2

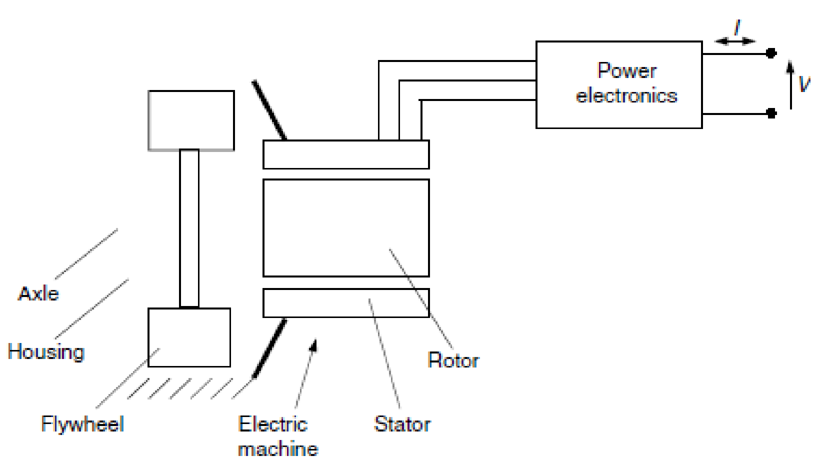
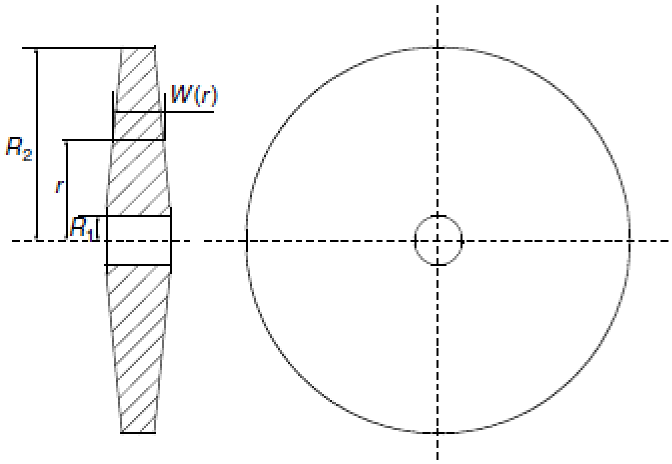


FIGURE 4.17: Basic structure of a typical flywheel system (mechanical battery)



where ρ is the material mass density and $W(r)$ is the width of the flywheelcorresponding to the radius r, as shown in Figure 4.18. The mass of the flywheelcan be calculated by

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

. ...eq3

Thus, the specific moment of inertia of a flywheel, defined as the moment ofinertia per unit mass, can be expressed as

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

...........................eq4

Equation (1) indicates that the specific moment of inertia of a flywheel isindependent of its material mass density and dependent solely on its geometricshape $W(r)$.
For a flywheel with equal width, the moment of inertia is

$$J_f = 2\pi\rho\left(R_2^4 - R_1^4\right) = 2\pi\rho\left(R_2^2 + R_1^2\right)\left(R_2^2 - R_1^2\right).$$

............................eq5

The specific moment of inertia is

$$J_{fs} = R_2^2 + R_1^2.$$

..........................eq6

The volume density of the moment of inertia, defined as the moment of inertiaper unit volume, is, indeed, associated with the mass density of the material.
The volume of the flywheel can be obtained by

$$V_f = 2\pi\int_{R_2}^{R_2} W(r)r\,dr.$$

.........................eq7

The volume density of the moment of inertia can be expressed as

$$J_{fV} = \frac{\rho\int_{R_1}^{R_2} W(r)r^3\,dr}{\int_{R_1}^{R_2} W(r)r\,dr}.$$

...............................eq8

For a flywheel with equal width, the volume density of the moment of inertiaIs

$$J_{fV} = \rho\left(R_2^2 + R_1^2\right).$$

. ... eq9

Equations (8) and (9) indicate that heavy material can, indeed, reduce the volume of the flywheel with a given moment of inertia.

POWER CAPACITY OF FLYWHEEL SYSTEMS:

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

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

.... eq10

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. Equation (10.44) indicates that the power capacity of a flywheel system depends completely on the power capacity of the electric machine. An electric machine usually has the characteristics as shown in

— constant torque and cregion.

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 isconstant. However, in the constant power region, the voltage is constant and the magnetic field is weakened with increasing machine angular velocity. In charge of the flywheel, that is, accelerating the flywheel from a low speed, ω0, to a high speed, maximum speed, ω*max*, for example, the torque delivered from the electric machine is

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

.... eq11

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

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

. ... eq12

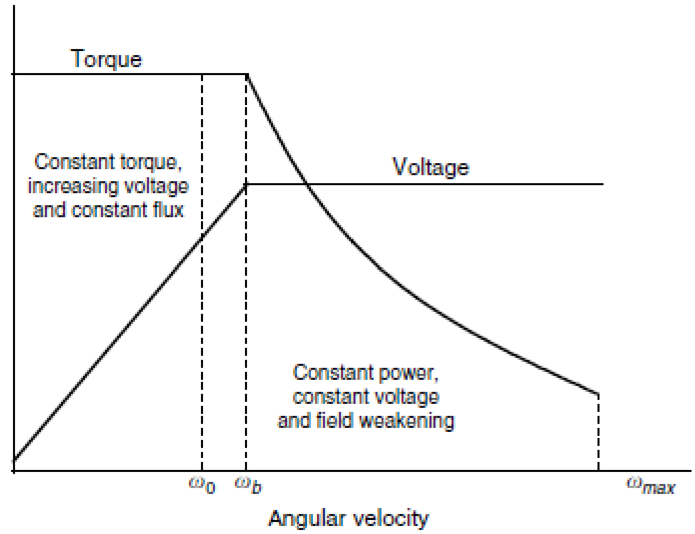


FIGURE 4.19. Typical torque and voltage profile vs. rotational speed

With the given accelerating time, *t*, the maximum power of the electricmachine can be obtained from (12) as

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

.... eq13

Equation (13) indicates that the power of the electric machine can be minimized by the design of its corner speed or base speed, ω*b*, 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

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

.... eq14

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 (refer to Figure 4.19), therefore significantly simplifying the power management system, such as DC/DC converters and their controls.

FLYWHEEL TECHNOLOGIES:

Although higher rotational speed can significantly increase the stored energy (equation [10.35]), there is a limit to which the tensile strength σ ofthe material constituting the flywheel cannot withstand the stress resulting from the centrifugal force. The maximum stress acting on the flywheeldepends 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 energy is

proportional to the ratio of σ/ρ. Table 10.4 summarizes thecharacteristics of some composite materials for ultrahigh-speed flywheels. A constant-stress principle maybe employed for the design of ultrahigh speedflywheels. To achieve the maximum energy storage, every element inthe 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. 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. On the contrary, the PM brushless motor shows some difficulty in weakening the field flux induced by the PM. In contrast to applying the ultrahigh-speed flywheel for energy storage in stationary plants, its application to EVs and HEVs suffers from two specific problems. First, gyroscopic forces occur whenever a vehicle departs from its straight-line course, such as in turning and in pitching upward or downward

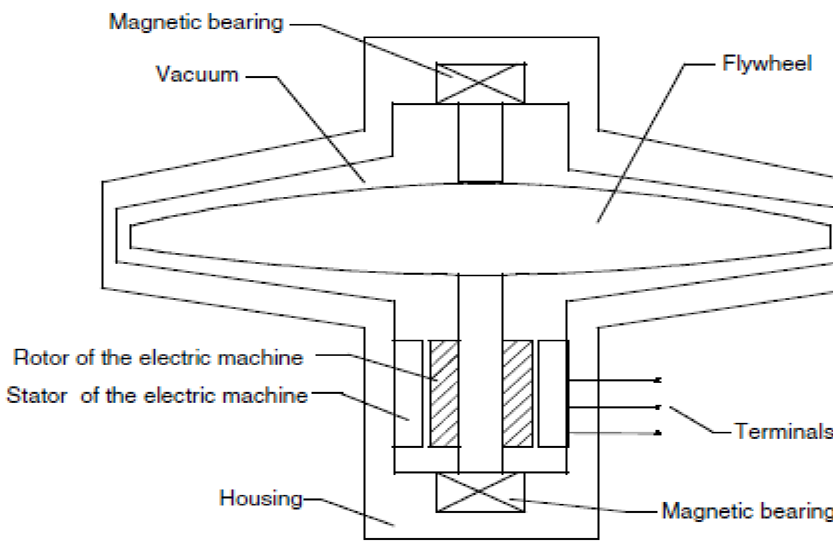


FIGURE4.20. Basic structure of a typical flywheel system

from road grades. These forces essentially reduce the manoeuvrability of the vehicle. Secondly, if the flywheel is damaged, its stored energy in mechanical form will be released in a very short period of time. The corresponding power released will be very high, which can cause severe damage to the vehicle. For example, if a 1-kWh flywheel breaks apart in 1 to 5 sec, it will generate a huge power output of 720 to 3600 kW. Thus, containment in case of failure is presently the most significant obstacle to implementing the ultra-high speed flywheel in EVs and HEVs.

The simplest way to reduce the gyroscopic forces is to use multiple smaller flywheels. By operating them in apair (one half spinning in one direction and another in the opposite direction), the net gyroscopic effect becomes theoretically zero. Practically, it still has some problems related to the distribution and coordination of these flywheels. Also, the overall specific energy and specific power of all flywheels may be smaller than a single one. Similarly, the simplest way to minimize the damage due to the breakage ofthe ultrahigh-speed flywheel is to adopt multiple small modules, but

specific power. Recently, a new failure containment has beenproposed. Instead of diminishing the thickness of the rotor's rim to zerobased on the maximum stress principle, the rim thickness is purposely enlarged. Hence, the neck area just before the rim (virtually a mechanical fuse) will break first at the instant that the rotor suffers from a failure. Dueto the use of this mechanical fuse, only the mechanical energy stored in therim needs to be released or dissipated in the casing upon failure.6Many companies and research agencies have engaged in the development ofultrahigh- speedflywheels as the energy storages of EVs and HEVs, such as Lawrence Livermore National Laboratory (LLNL) in the U.S., Ashman Technology, AVCON, Northrop Grumman, Power R&D, Rocketdyne/Rockwell Trinity Flywheel US Flywheel Systems, Power Centre at UT Austin, etc. However, technologies of ultrahigh-speed flywheel are still in their infancy. Typically, the whole ultrahigh-speed flywheel system can achieve a specific energy of 10 to 150 Wh/kg and a specific power of 2 to 10 kW. LLIL has built prototype (20 cm diameter and 30 cm height) that can achieve 60,000 rpm,1 kWh, and 100 kW.

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, thereforeachieving 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 Figure 10.18. In high power demand operations, such as acceleration and hill climbing, both basic energy storages deliver their power to the load as shown in Figure 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). In regenerative brakingoperations, the peak power will be absorbed by the high specific

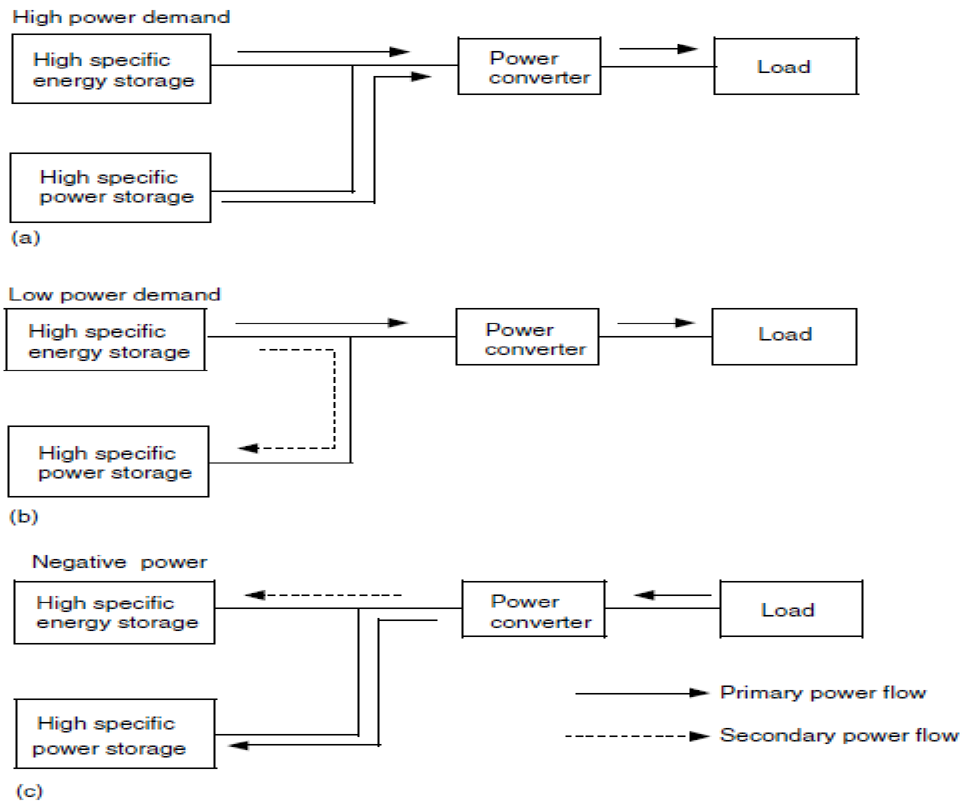


FIGURE 4.21. Concept of a hybrid energy storage operation

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

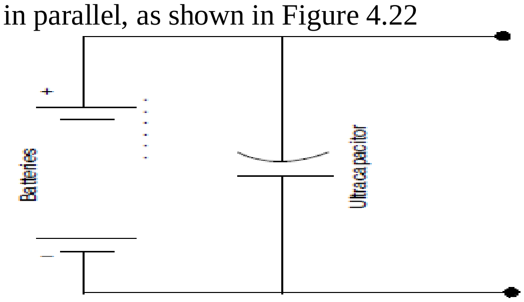
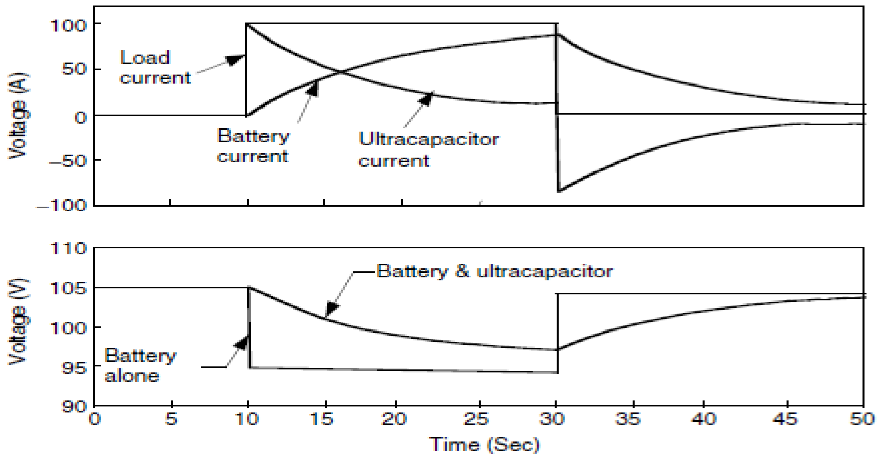
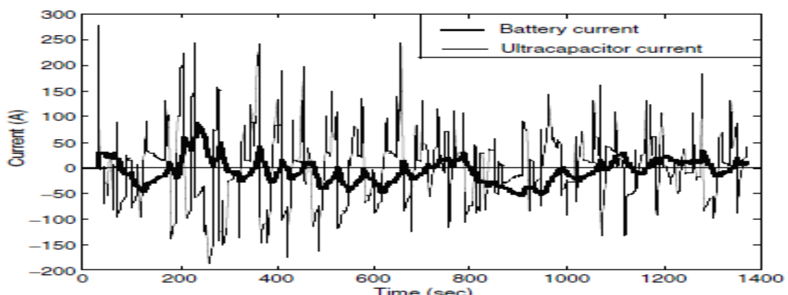


FIGURE 4.22. Direct and parallel connection of batteries and ultra capacitors

FIGURE 4.23. Variation of battery and ultra capacitor currents and voltages with a step current output change





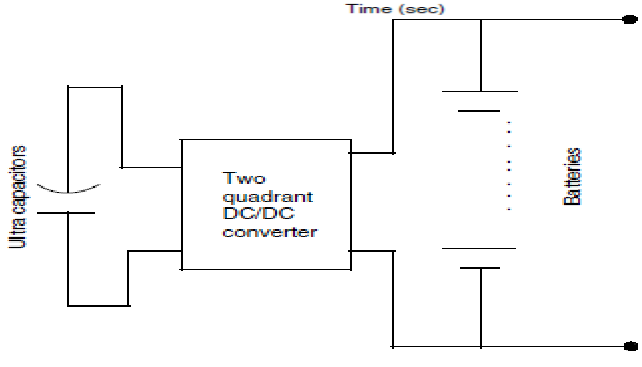


FIGURE 4.25. Actively controlled hybrid battery/ultracapacitor energy storage

In this configuration, the ultracapacitors simply act as a current filter, which can significantly level the peak current of the batteries and reduce the battery voltage drop as shown in Figure 10.20 and Figure 4.25. The major disadvantages of this configuration are that the power flow cannot be actively controlled andthe ultracapacitor energy cannot be fully used. Figure4.25 shows a configuration in which a two-quadrant DC/DC converter is placed between the batteries and ultracapacitors. This design allows the batteries and the ultracapacitors to have a different voltage, the power flow between them can be actively controlled, and the energy in the ultracapacitors can be fully used. In the long term, an ultrahigh-speed flywheel would replace the batteries in hybrid energy storage to obtain a highefficiency,compact, and long-life storage system for EVs and HEVs.

UNIT –V

ENERGY MANAGEMENT STRATEGIES

CLASSIFICATION OF HYBRID ECU:

The hybrid ECU(**electronic control unit**) is the heart of the control architecture of any HEV and it is also known energy management strategy (EMS). The EMS can be classified into following broad categories:

I. **Rule based**

II. 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

The Optimization based strategies are of following types:

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

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.

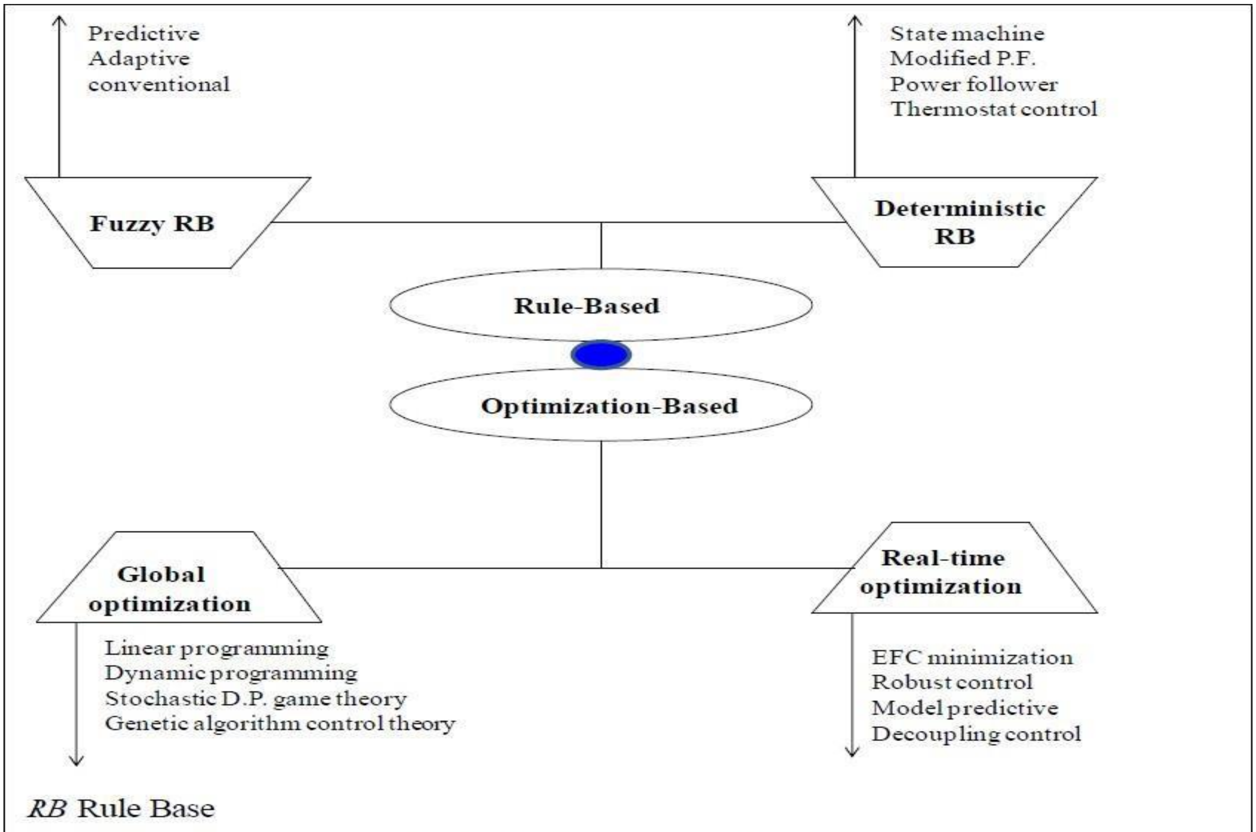


Figure 1: Classification of control strategies [1]

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.

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.

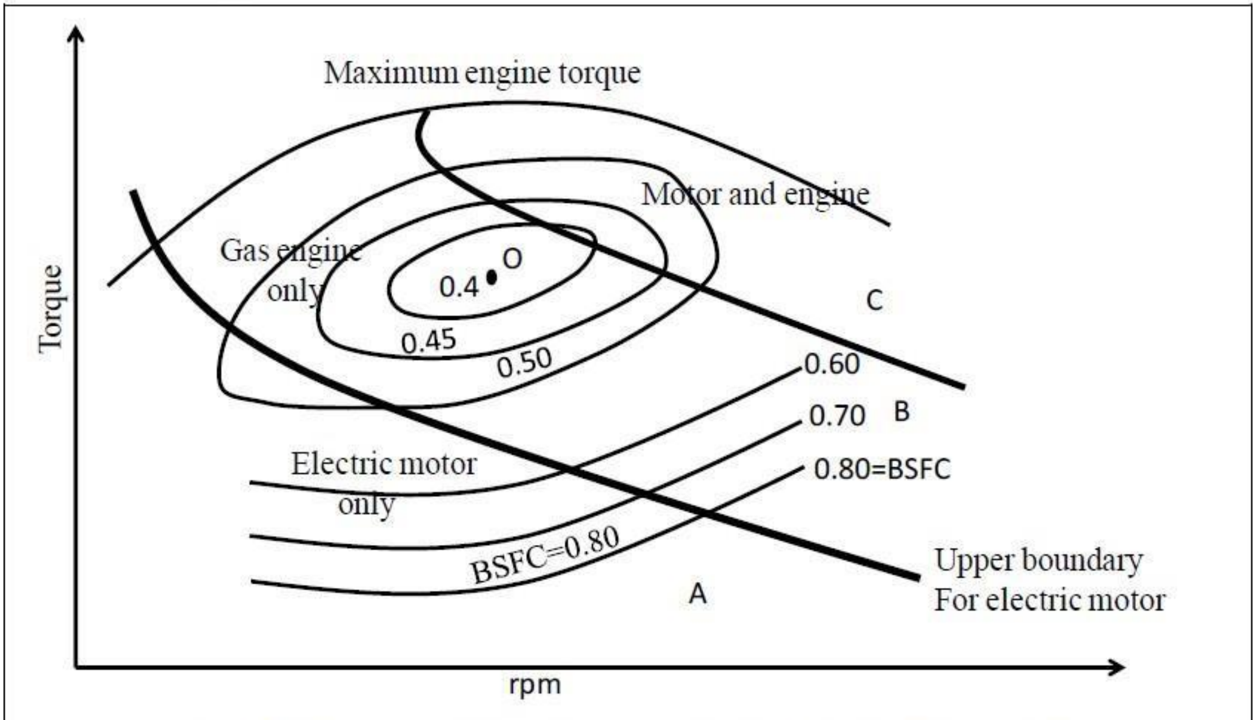


Figure 3: Efficiency map of ICE showing upper and lower boundaries for EM operation [1]

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.

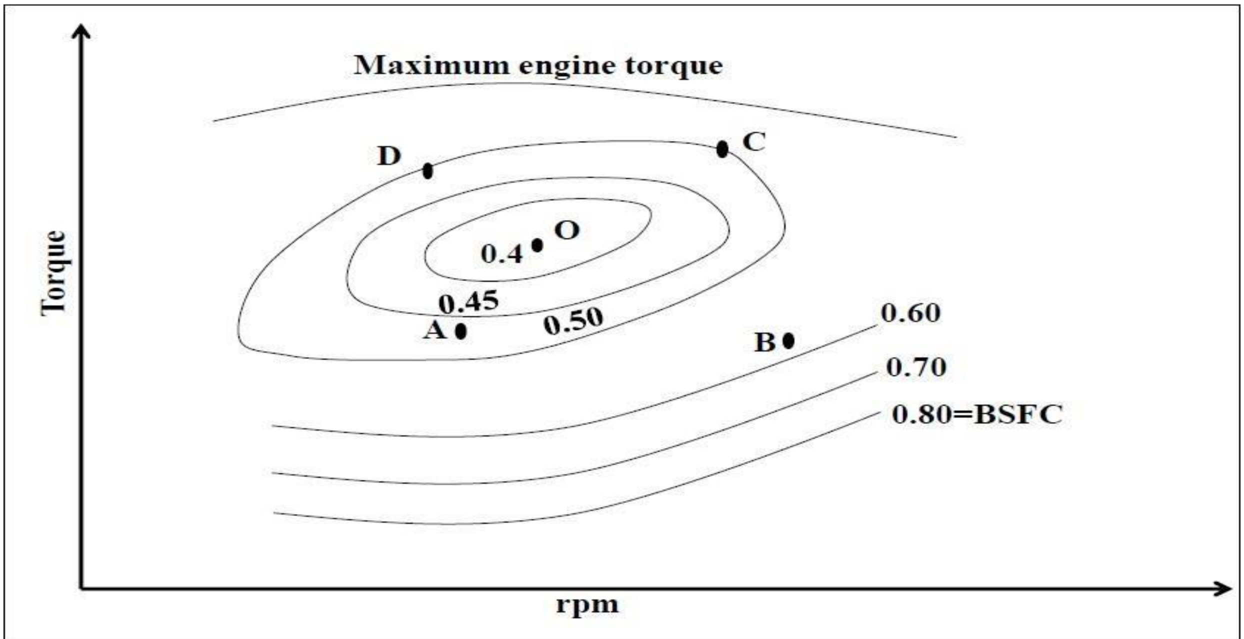


Figure 2: Efficiency map of ICE [1]

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

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

$$\text{where}$$

$$K = \text{ motor to ICE gear ratio}$$

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 ofoperating 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

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

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

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

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

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

1

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

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

1

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

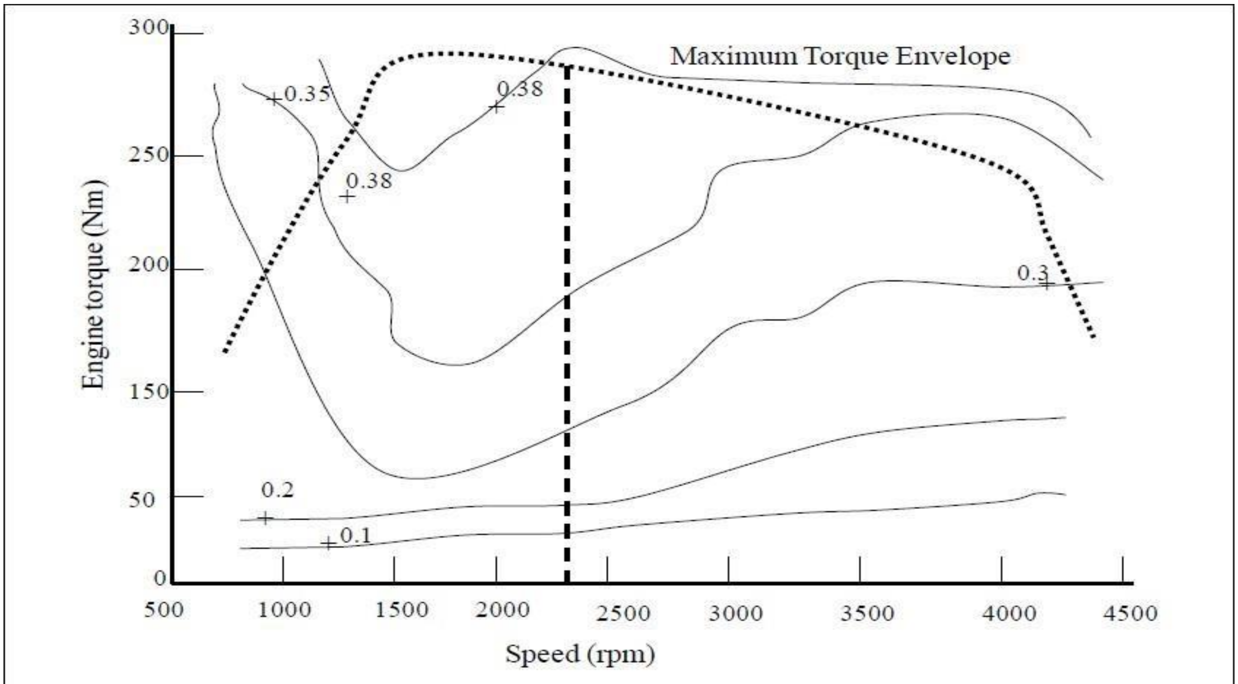


Figure 4: Efficiency map for hot ICE [1]

NORMALIZE THE CONSTITUENT FACTORS FOR EACH CANDIDATE OPERATING POINT:

The goals of minimizing energy and minimizing emissions can conflict with each other. The most efficient operating point will likely produce more pollution than less efficient operating points.

Moreover, minimizing the amount of one pollutant can increase the amount of another. Hence, a second goal of the strategy is to allow prioritization of the relative importance of minimizing the fuel use and each of the pollutants. This prioritization is described in Steps 4 and 5 below. Apply user weighting to the results from step iii.: The relative importance of each of the normalized metrices is determined by two weighing factors. The first is a user weighing fore energy and the emissions. This is basically a Boolean switch for the user to toggle if he/she chooses to ignore certain emissions. User K

Apply target performance weighting: The target performance weighing factor is applied to result from step iv. The factor is given by t

$$K_{\text{target}} = \frac{\text{max of time averaged vehicle performance}}{\text{target performance}}$$

Compute overall impact factor, which is a composite of results of **step iii** to **step v** for all operating points, that is

$$\text{Impact} = \frac{\sum\left(K_{user}^{*} K_{\text{target}}^{*} \text{normalized\_variables}\right)}{\sum\left(K_{user}^{*} K_{\text{target}}^{*}\right)}$$

The flow chart of the control strategy is shown in **Figure 5**.

The final operating point is the operating point with the minimum impact factor. This strategyimproves the overall performance of the HEV drive train but is computationally expensive

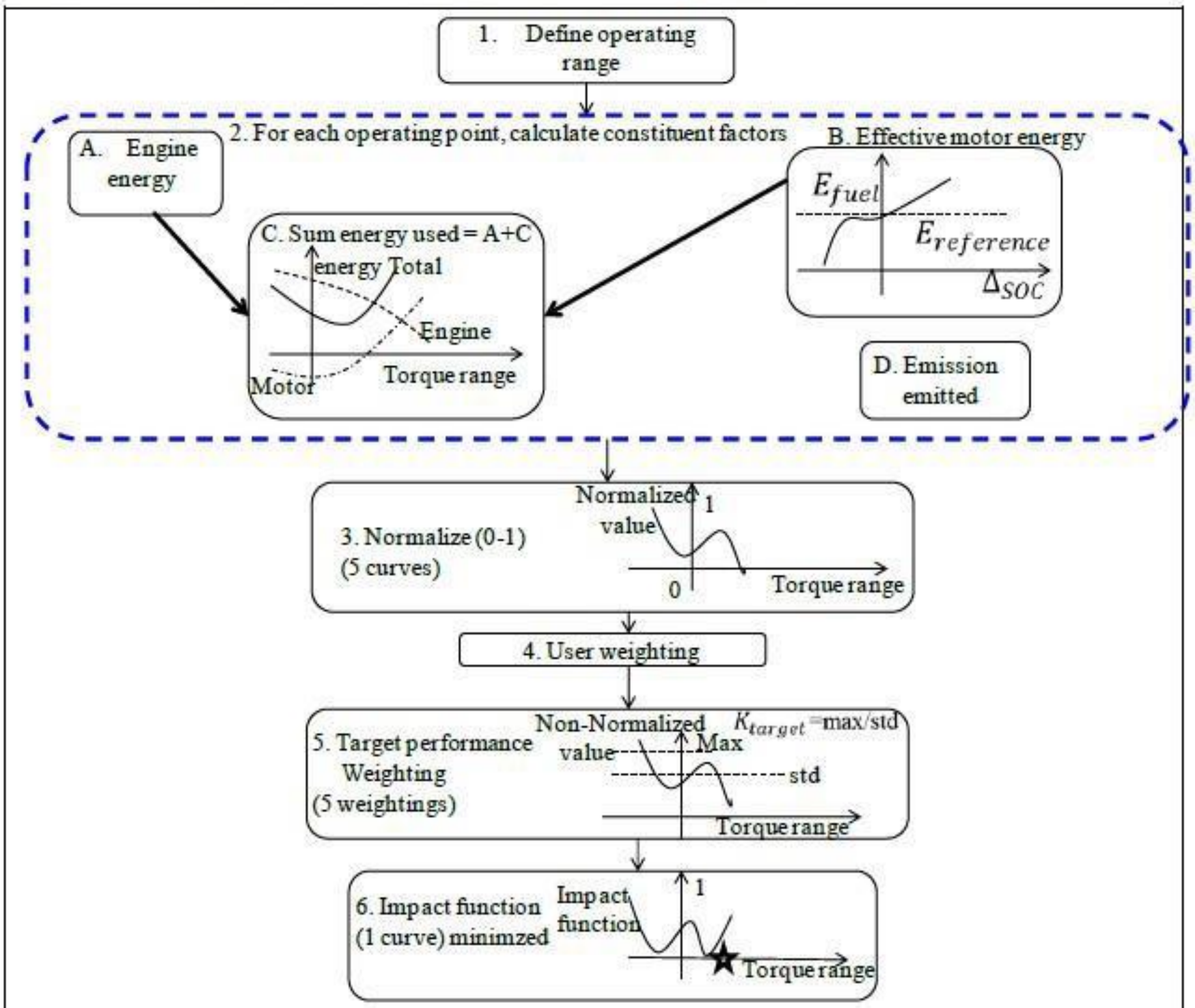


Figure 5: Flow chart for modified power follower controller strategy [1]

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.

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

Implementation of a vehicle controller through state machines facilitates fault resilient supervisory control of the whole system.