

ELECTRIC & HYBRID VEHICLE AND EMISSION CONTROL

LECTURE NOTES

6TH SEMESTER



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Electric Vehicle

Electric vehicles are defined as vehicles which use an electric motor for propulsion. Electric vehicle is propelled by one or more electric motors, receiving power from an onboard source of electricity such as batteries, fuel cells, ultracapacitor, flywheel, etc.

The electrical energy from the onboard source of electricity is used to power an electric motor, which then turns the wheels and provides propulsion.

EVs include a large range of vehicles from electric two-wheelers, three-wheelers (rickshaws), cars and electric buses and trucks.

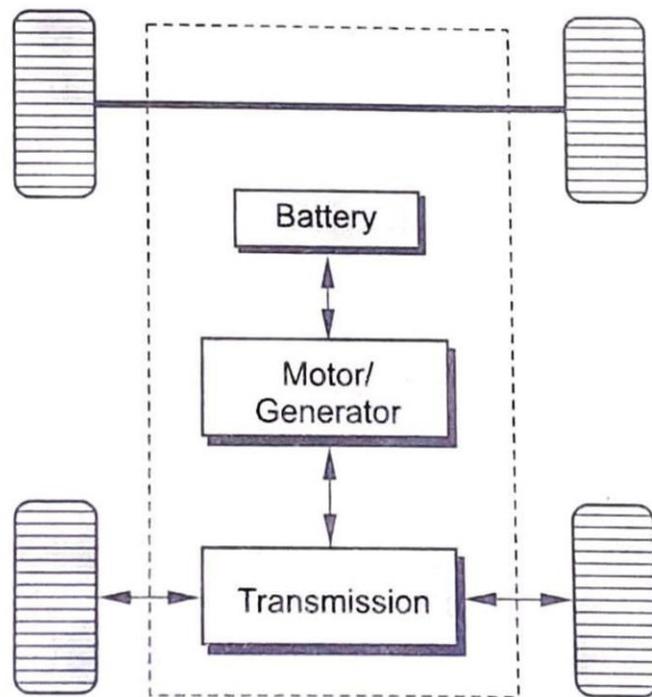


Fig.3.1: Layout of an electric vehicle

NEED FOR ELECTRIC VEHICLE

The main reasons for the need of electric vehicles are:

- Depletion of oil reserves
- Stringent emission standards
- Noise pollution

There would be no exhaust emissions emitted from electric drives. This zero emission vehicles are almost noiseless and can be charged at home or work place. EVs are easier to service and maintain due to the absence of spark plugs, clutch and gears. They are ideal for 'stop-start' city driving conditions. EVs are extremely reliable and ease to drive.

It is known that almost any fuel can be used to generate electricity. Therefore our dependence upon petroleum can be reduced by switching to electric vehicles.

PROBLEMS OF ELECTRIC VEHICLES

The major concerns regarding EVs today is their driving range, charging time and efficiency of batteries. Much development is needed to find a higher energy, longer lasting battery, and to bring down costs if EVs are to compete successfully with conventional vehicles.

Range and batteries

The main problem with electric vehicles is the batteries used for energy storage. The current battery technology limits the distance an electric car can travel before its battery must be recharged. The present electric vehicles have a limited range of only 80 to 160 km, on the order of one-fifth of what can be easily realized with a gasoline engine powered vehicle.

In this case, the customers are forced to rely on the public charging points. Although the number of charging stations is increasing, it is still incomparable with the convenience of the petrol stations and their density. And accessories, such as air-conditioning or music system, drain the battery even more quickly. Batteries have about 1% of the energy per unit mass of a typical automotive fuel, and a life span of about 2-3 years. Batteries typically account for one-third or more of the vehicle weight. High capital cost of batteries is also a drawback.

A breakthrough in battery technology is required if electric vehicles are to become a significant part of the automotive transportation.

Approximate range for EVs on the market

EV model	Apprx. range on full charge
Tesla Model S	500 km
Nissan Leaf	151 km
BMW i3	190 km-petrol range extender option available

EV model	Apprx. range on full charge
Kia Soul	148km
Honda Fit	132km
Chevrolet Spark	132km
Ford Focus Electric	122km
BEV Electron	120km
Mitsubishi i-Miev	150km
Mitsubishi Outlander	50km electric only with the back-up of a 45 litre petrol engine

Charging

A majority of the EV owners (95%) usually charge their cars' batteries during the night, when they are not using the car. Charging at night when consumption is low, allows for efficient use of electricity. Anyway, not all the members of the population have the facility of parking in a garage. Many people park their cars in the street.

To charge the battery fully it takes about 6-7 hrs. The charging time is another issue, as charging time on the stations compared to refuelling diesel/petrol is high. This issue can be solved with the so-called rapid chargers, adding to the vehicle's range within less than an hour.

As battery types and battery technologies improve, the concerns regarding driving range and charging time will get further reduced.

Lack of performance

Electric cars are not able to accelerate, cruise, and climb fast enough when compared to gasoline-powered cars.

Purchase price

The purchase price of any electric car is generally much higher than any other conventional vehicle from given class and quality segment. The main reason for electric cars being so expensive is mainly their battery price.

Safety and reliability

The general perception among people is that EVs are not safe. Present EVs incorporate many safety features like the steel space frame,

side impact beams, dent-proof ABS body panels, low voltage system, and dual braking system. All these features lead to a very high level of reliability and safety. Today all EVs are safer than any of the conventional vehicles available on the road.

Fear of running out of charge in the middle of the road

Many customers have this fear that without proper warning the car will run out of charge leaving them stranded.

To counter this EVs incorporate a number of warnings to ensure that the customer gets ample warning signals in the form of a warning display on the instrument panel.

ADVANTAGES OF ELECTRIC VEHICLE

1. Mechanically simpler.
2. Running cost is 40 paise per kilometer.
3. Zero emission vehicle. Also reducing greenhouse emission.
4. They are very quiet in operation. While running, it does not produce noise and vibrations.
5. As there are no gears and clutch in these vehicles, they are extremely reliable, safe and easy to drive and manoeuvre in the congested cities.
6. Minimum maintenance and service as EVs have fewer moving parts.
7. Ideal for stop-start conditions.
8. More durable than gasoline-powered cars.
9. More energy efficient than gasoline engines.
10. Reduce dependency on imported energy sources.
11. Power regeneration.

DISADVANTAGES OF ELECTRIC VEHICLE

1. Vehicle range is limited on one charge. The vehicle can run 80-160 km on a single charge.
2. Top speed is limited.
3. It is heavy and bulky.
4. Limited public charging stations.

MAJOR COMPONENTS OF ELECTRIC VEHICLE

An electric vehicle consists of a battery that provides energy, an electric motor that drives the wheels, and a controller that regulates the energy flow to the motor. There are no gearbox and clutch in these vehicles.

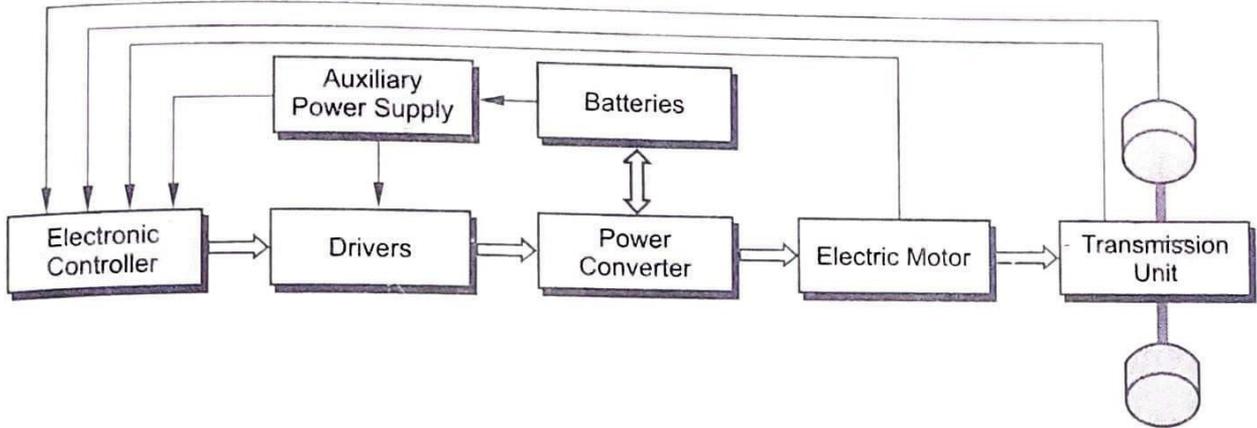


Fig.3.2: Major components in an electric vehicle

Motor

The prime mover in electric vehicle is the high-torque electric motor. The motor converts the energy stored in the power pack into mechanical motion. The high torque electric motor ensures a quick acceleration. The power from the motor is delivered to the wheels directly or through the transaxle that propels the vehicle. While braking, the motor acts like a generator (regenerative braking) and recharges the batteries.

There are several choices of the type of drive motor. The basic choice is between an AC and a DC motor. The AC motor offers many control advantages but requires the DC produced by the batteries to be converted using an inverter. A DC shunt wound motor rated at about 50 kW is a popular choice for the smaller vehicles but AC motors are likely to become the most popular. REVA has a 13 kW separately excited DC motor with a high torque of 70 Nm at zero speed.

Power pack (Battery)

Automobile manufacturers use three types of rechargeable battery for electric car use. Those types are lead-acid batteries, nickel metal hydride (NiMH) batteries, and lithium-ion (Li-ion) batteries. The space occupied by these heavy batteries is large. Operational problems include the limited range of the vehicle and its comparatively low maximum speed. Currently the main advantage of lead-acid batteries is the existing mature technology, which is accepted by the motor industry.

REVA's Power Pack consists of eight 6-Volt EV tubular type lead acid batteries that attain 80 percent state of charge (quick-charge mode)

in under 2.5 hours. A complete charge is achieved in less than seven hours and gives a range of 80 km. The power pack is housed beneath the front seats, which lowers the center of gravity, thus increasing the safety of passengers. Charging REVA is a safe and easy process - just plug into a 220 Volt, 15 Ampere socket at home or at work. A full charge consumes just about 9 units of electricity.

Charger

EVs have an on-board charger, which converts AC into DC power to charge the power pack. The charger is computer controlled with an in-built stabilizer and auto shut-off mechanism. The smart charger's output is connected to the power pack and ensures that optimum current and voltage is maintained at all times.

Controller

EVs also have a computerised motor controller. This regulates the flow of energy from the power pack to the motor in direct relation to pressure applied on the accelerator. It ensures perfect speed control and optimum use of energy in both forward and reverse directions. Speed controllers are rated according to the voltage and amperage ranges.

DC/DC converter

A 12 V auxiliary battery is normally used in an electric car to power all 12 V accessories such as lights, horn and so on. There is no alternator in EVs to keep this battery charged. EVs use a DC/DC converter which taps the full battery pack voltage and cuts it down to a regulated 13.5 V output, similar to an alternator. It is not advisable to eliminate the auxiliary battery completely, for safety reasons. If the DC/DC converter fails at night or the battery pack falls below the low voltage shut-off of the converter, the auxiliary battery will have enough charge to bring the car home.

Energy Management System (EMS)

The brain of EVs is the Energy Management System (EMS) that monitors and controls all required functions. The EMS is a computer-based system that optimises charging and energy output of batteries to maximise operating range and improve performance. The EMS increases the electric vehicle range by 10–15% and battery life by 25–30%.

The system also predicts available range for a given state of battery charge. The EMS also maintains an electronic log of the vehicle performance, enables service personnel to run diagnostic checks on the car to give service information about the car.

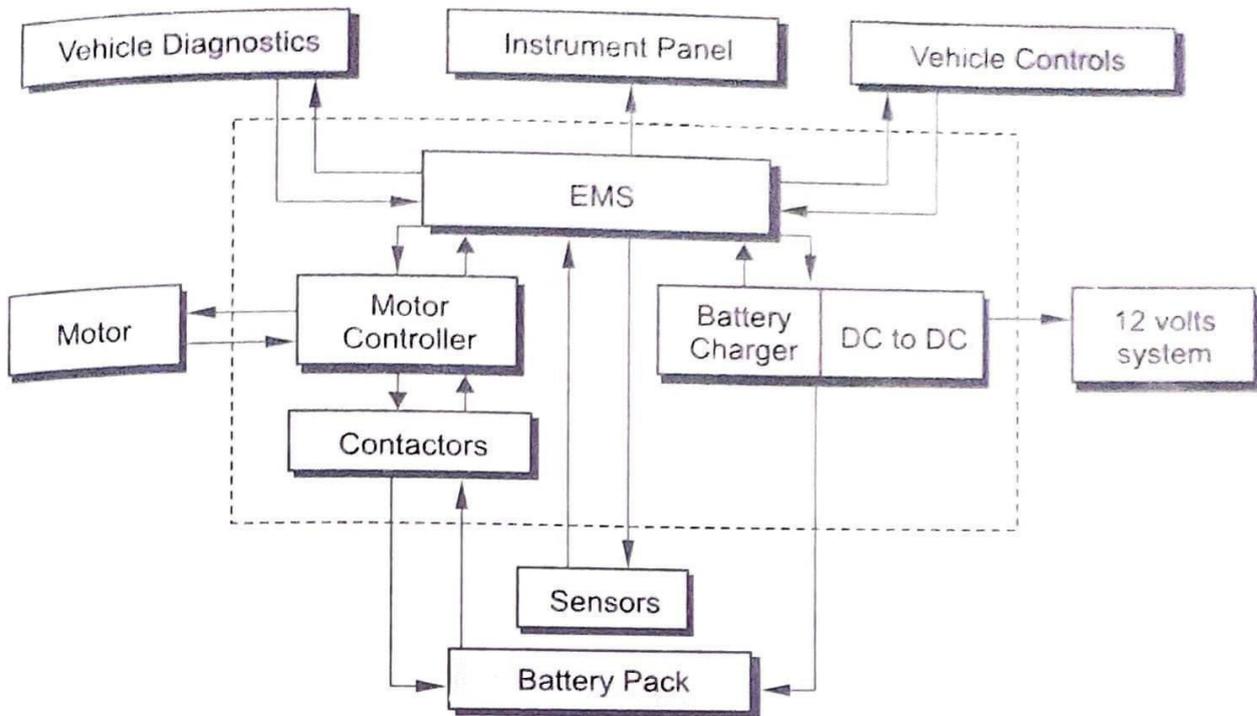


Fig.3.3: *Energy management system*

Compared with Internal Combustion Engine Vehicles (ICEVs), EVs offer a relatively short driving range. Thus, in order to maximize the utilization of on-board stored energy, an intelligent energy management system (EMS) needs to be adopted. Making use of sensory inputs from various EV subsystems, including sensors for temperatures of outside and inside air, current and voltage of the energy source during charging and discharging, current and voltage of the electric motor, vehicle speed and acceleration as well as external climate and environment, the EMS can realise the following functions:

- To optimize the system energy flow.
- To predict the remaining available energy and hence the residual driving range.
- To suggest more efficient driving behaviour.
- To direct regenerative energy from braking to receptive energy sources such as batteries .
- To modulate temperature control in response to external climate.
- To adjust lighting brightness in response to external environment.
- To propose a suitable battery charging algorithm.
- To analyse the operation history of the energy source, especially the battery.
- To diagnose any incorrect operation or defective components of the energy source.

When the EMS is coupled with a navigation system, it can plan energy efficient routes, locate charging facilities for extended trips, and modify range predictions on the basis of traffic conditions. In summary, the EMS has the distinct features of integrated multi-functions, flexibility and adaptability (just like the brain of EVs) such that the limited on-board energy can be used wisely.

Classification of EVs

EVs can be classified on the basis of their attributes such as i) charging time, ii) driving range, and iii) the maximum load it can carry.

Charging time (i.e. the time required to fully charge the battery)

A measure of the time taken to charge the battery to 100% from 0%. Charging time depends on the input power characteristics (i.e. input voltage and current), battery type, and battery capacity. The charging time is typically less than 8 hours, but for some vehicles the charging time tends to be higher.

Driving range (i.e. the maximum distance an EV can run when fully charged)

A measure of the distance electric vehicles can cover on a single charge of battery. The driving range of EVs could be as low as 20 km per charge to as high as 400 km per charge.

Pay load capacity

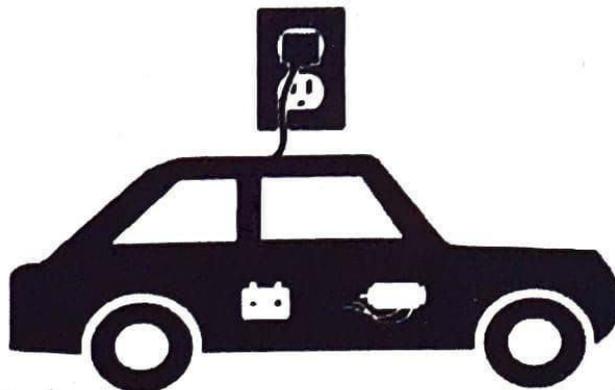
A measure of the maximum load (weight) a vehicle can carry.

CLASSIFICATION

There are 3 types of electric vehicle: Battery Electric Vehicle (BEV), Hybrid Electric Vehicle (HEV), and Plugin Hybrid Electric Vehicle (PHEV) and each are described in more detail below.

ACCORDING TO THE SOURCE OF POWER

Battery Electric Vehicle (BEV)



A battery electric vehicle (BEV) runs entirely using an electric motor and battery, without the support of a traditional internal combustion engine, and must be plugged into an external source of electricity to recharge its battery. Like all electric vehicles, BEVs can also recharge their batteries through a process known as regenerative braking, which uses the vehicle's electric motor to assist in slowing the vehicle, and to recover some of the energy normally converted to heat by the brakes. Fig.4.1 shows basic configuration for BEVs: the wheels are driven by electric motor(s) which is run by batteries through a controller circuit.

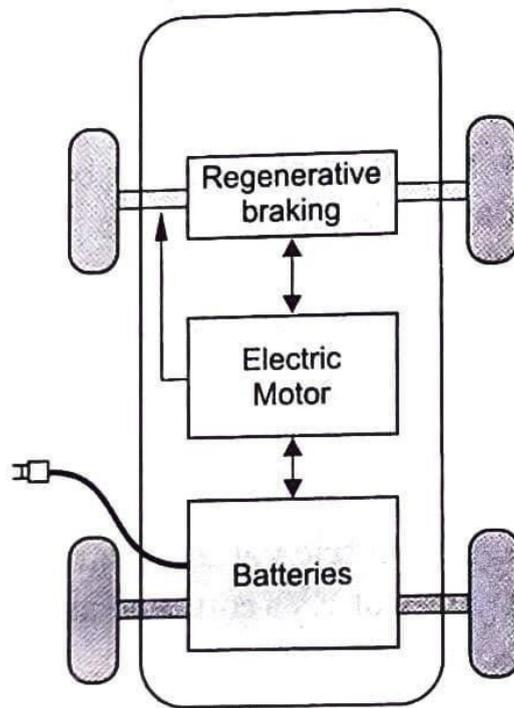


Fig.4.1: Basic configuration for BEVs

BEVs have to rely solely on the energy stored in their battery packs; therefore the range of such vehicles depends directly on the battery capacity.

Typically they can cover 100 km - 250 km on one charge, whereas the top-tier models can go a lot further, from 300 km to 500 km. These ranges depend on driving condition and style, vehicle configurations, road conditions, climate, battery type and age. Once depleted, charging the battery pack takes quite a lot of time compared to refueling a conventional internal combustion engine vehicle.

It can take as long as 36 hours completely replenish the batteries, there are far less time consuming ones as well, but none is comparable to the little time required to refill a fuel tank. Charging time depends on the charger configuration, its infrastructure and operating power level.

Vehicle model	Range	Charge time
Tesla Model S	335 – 426 km	5 hours
Nissan Leaf	120 km	3 hours
BMW i3	160 km	6 hours
Mitsubishi iMi	100 km	7 hours
Smart	109 km	6 hours
Ford Focus	110 km	4 hours

Advantages

- No emissions while running
- Silent
- No gas or oil changes
- Ability to conveniently charge at home
- Fast and smooth acceleration
- Low cost of operation
- Instant and high torques, even at low speeds

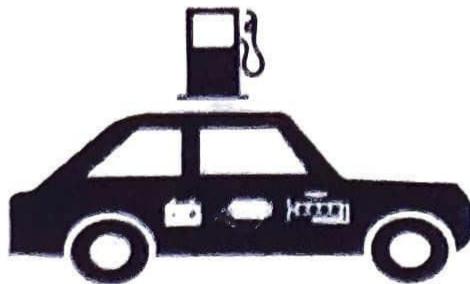
Disadvantages

- Shorter range than gasoline vehicles although most people drive well within the range of today's BEV and could rent a hybrid for the rare long trips.
- Slightly more expensive than their gasoline equivalent although the gasoline savings pay off the difference in typically 2-3 years.

Application

Nissan Leaf and Teslas are some high-selling BEVs these days, along with some Chinese vehicles.

Hybrid Electric Vehicle (HEV)



Hybrid Electric Vehicles (HEVs) produce supplemental fuel source to produce electricity on-board. HEVs have two complementary drive systems: a gasoline engine with a fuel tank; and an electric motor with a battery. Both the engine and the electric motor can turn the transmission

at the same time, and the transmission then turns the wheels. HEVs cannot be recharged from the electricity grid – all their energy comes from gasoline and from regenerative braking. Fig.4.2 shows basic configuration for HEVs: the wheels are driven by both electric motor(s) and internal combustion engine through a controller circuit.

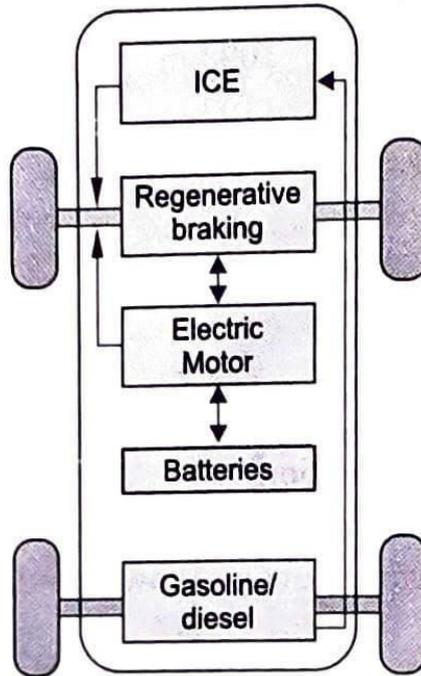


Fig.4.2: Basic configuration for HEVs

An HEV uses the electric propulsion system when the power demand is low. It is a great advantage in low speed conditions like urban areas; it also reduces the fuel consumption as the engine stays totally off during idling periods, for example, traffic jams. This feature also reduces the greenhouse gas emission. When higher speed is needed, the HEV switches to the engine mode. The two drive trains can also work together to improve the performance.

Vehicle model	Range	Charge time
Audi Q5 Hybrid	NA	NA
BMW Active Hybrid	NA	NA
Honda Civic Hybrid	NA	NA
Hyundai Sonata Hybrid	NA	NA

Hybrid power systems are used extensively to reduce or to completely remove turbo lag in turbocharged cars, like the Acura NSX. It also enhances performance by filling the gaps between gear shifts and providing speed boosts when required. The internal combustion engine can charge up the batteries, HEVs can also retrieve energy by means of regenerative braking. Therefore, HEVs are primarily engine driven cars

that use an electrical drive train to improve mileage or for performance enhancement. To attain these features, HEV configurations are being widely adopted by car manufacturers.

A typical hybrid electric vehicle is fuelled by gasoline and uses a battery-powered motor to improve efficiency, thus is not considered a plug-in electric vehicle. The battery in a gasoline hybrid is never plugged into an electrical outlet, but instead is powered by a combination of the gasoline engine and regenerative braking.

Advantages

1. Low exhaust emission levels than internal combustion engines.
2. Increased range compared to electric vehicles.
3. Engines can be down sized to accommodate average load, not peak load, which reduces the engine's weight.
4. Fuel efficiency is greatly increased.
5. Emissions are greatly decreased.

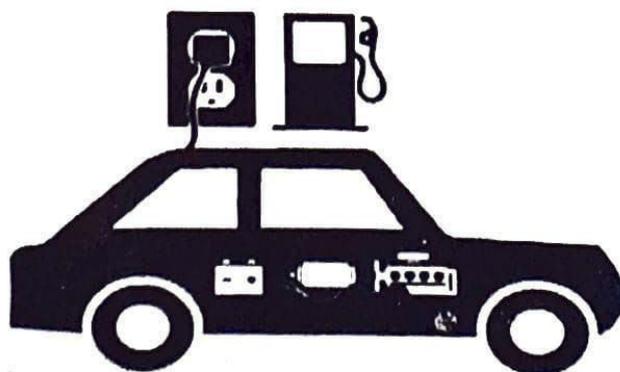
Disadvantages

6. Bulky and heavy.
7. Require very complicated control systems.
8. Cost is very high.

Application

The most well known hybrid electric vehicle is the Toyota Prius.

Plug-In Hybrid Electric Vehicle (PHEV)



Plug-in hybrids (PHEVs) use an electric motor and battery that can be plugged into the power grid to charge the battery, but also have the support of an internal combustion engine that may be used to recharge the vehicle's battery and/or to replace the electric motor when the battery is low. Because Plug-in Hybrids use electricity from the power grid, they often realise more savings in fuel costs than traditional hybrids electric vehicles (HEV).

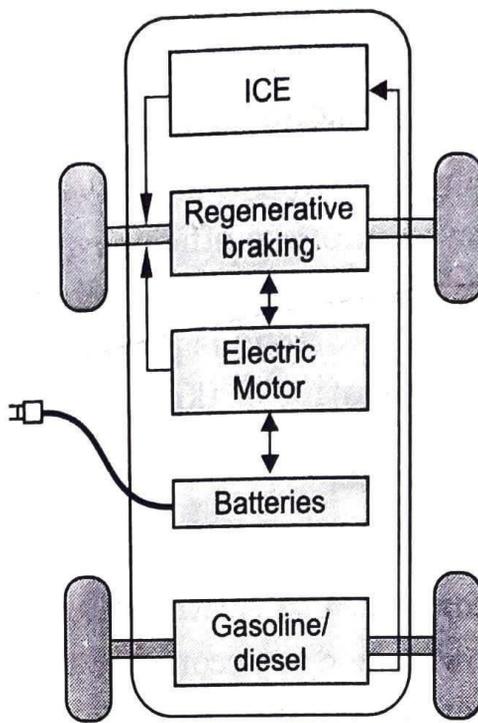


Fig.4.3: Plug-in hybrid electric vehicle

Vehicle model	Range	Charge time
BMW i3	160 km on electric, 160 on petrol	6 hours
Cadillac ELR	59 km on electric, 488 km on petrol	2 hours
GM Chevy Volt	60 km on electric, 500 km on petrol	2 hours
Ford Fusion Energi	34 km on electric,	2-3 hours
Toyota Prius Plugin	18 km on electric	1-2 hours

These vehicles generally run on the electric motor until the battery is depleted, at which point the engine can kick in, extending the car's range.

Advantages

- Longer range than BEV
- Less gas consumption than gas only vehicle
- Fewer emissions
- Very simple mechanics, less to go wrong.

Disadvantages

- Produces tailpipe emissions
- Needs gas and oil changes
- More expensive to operate than Battery Electric Vehicle (BEV) but less than traditional hybrid vehicle (HEV).

Application

An example of a plug-in hybrid is the Chevrolet Volt.

ACCORDING TO DRIVE ARRANGEMENT

Conventional type

Conventional type uses traditional transmission (gearbox) in the drivetrain system of an electric vehicle.

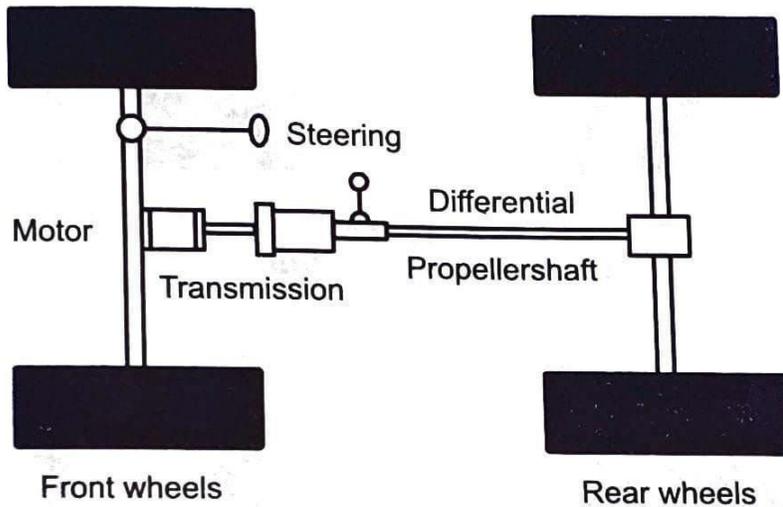


Fig.4.4: Conventional type

No-transmission type

In a no-transmission type, there is no conventional gearbox. Motor torque is transmitted to the wheels through propeller shaft and differential assembly.

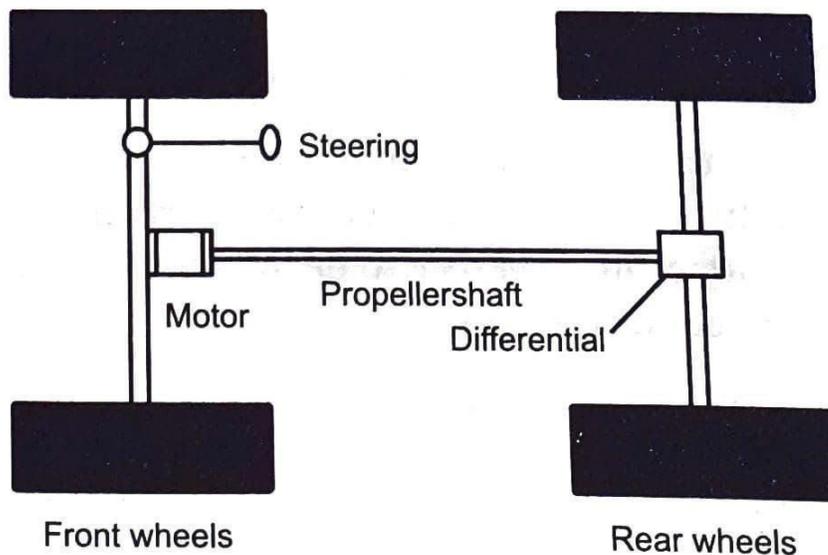


Fig.4.5: No-transmission type

No-differential type

Each wheel has an individual motor and hence differential is not required.

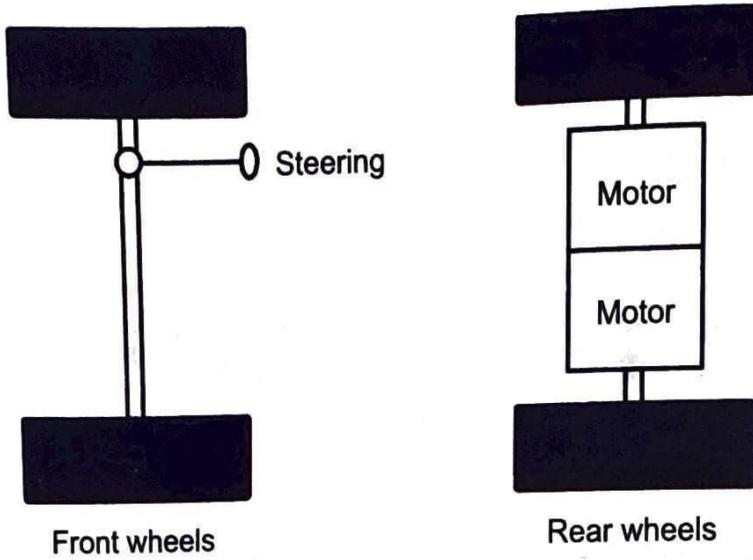


Fig.4.6: No differential type

In-wheel motor type

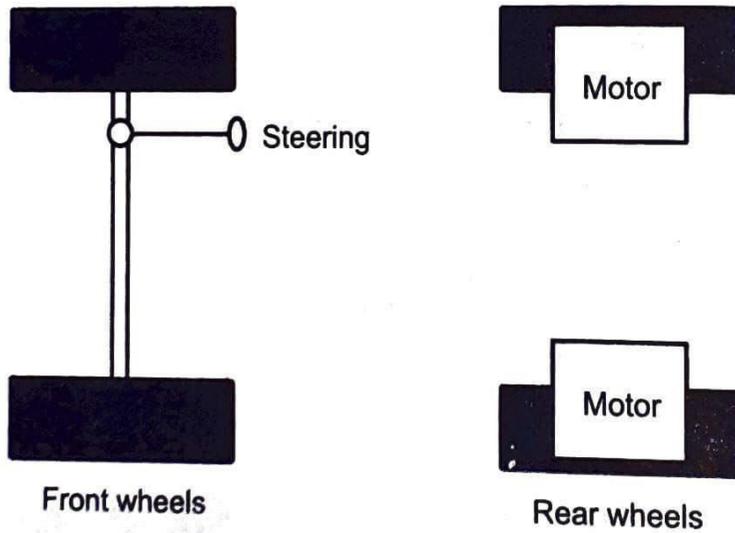


Fig.4.7: In-wheel motor type

The in-wheel motor EV installs motors right around each of the driving wheels to directly power the wheels. Also there is no need for a differential as the amount of power to each wheel can be controlled by the separate in-wheel electric motors.

In addition to good accelerator responsiveness, an advantage of EVs, the in-wheel motor makes the behaviour of the car more in tune with the steering by independently controlling the left and right wheels. When accelerating or cornering, the car moves intuitively in the way the driver wants.

Energy Sources

EVs can get the energy required to run from different sources. EVs use different types of energy storage to store their power. They include:

- Batteries
- Ultra capacitors
- Flywheels
- Fuel cells

Requirements of EVs energy sources

The criteria such sources have to satisfy are:

1. High specific energy and energy density
2. High specific power and power density
3. Fast charging and deep discharging capabilities
4. Long cycle and service lives
5. Low self discharging rate and high charging efficiency
6. Safety and cost effectiveness
7. Maintenance free
8. Environmental sound and recyclable

High specific energy is required from a source to provide a long driving range whereas high specific power helps to increase the acceleration. The other characteristics that make a perfect energy source are fast charging, long service and cycle life, less cost and maintenance.

BATTERY

Batteries have been the major energy source for EVs for a long time. The battery converts stored chemical energy into electric energy. The chemical reaction between the electrodes and electrolyte generates electricity. Rechargeable batteries can reverse the chemical reaction by reversing the current. This way the battery can be recharged.

Battery is the most important component of an electric vehicle and typically constitutes up to about half of the vehicle cost and weight. The choice of batteries depends on the energy density, weight and costs.

Electric cycles and low range mopeds have simple battery units while electric cars deploy a large number of batteries.

Requirement of EV batteries

The batteries should have

1. A stable voltage output over a good depth of discharge
2. High energy capacity for the given battery weight and size
3. High peak power output per unit mass and volume
4. High energy efficiency
5. Able to function with wide ranges of operating temperatures
6. Good charge retention on open-circuit stand
7. Ability to accept fast recharge
8. Ability to withstand overcharge and over discharge
9. Reliable in operation
10. Maintenance free
11. Rugged and resistant to abuse
12. Safe both in use and accident conditions
13. Made of readily available and inexpensive materials with environmental friendliness
14. Efficient reclamation of materials at the end of service life

Selection of battery

This depends on mainly the voltage. The higher the voltage, the better the acceleration, and a higher top speed can be achieved. A normal sized EV using a voltage system of 96-120V with 6 deep-cycle batteries will give more amphere hours and weigh more. Therefore, it will have a fairly high range but poor performance. The same vehicle using a voltage system of 96-120 with 12V batteries will give high performance, but lower range. That is because the battery pack will be lighter and in turn the vehicle will be lighter.

Deep-cycle batteries

Deep-cycle batteries are normally available in three voltage sizes: 6, 8 and 12V. For range, 6V batteries are used because of their high specific energy. For performance, 12V batteries are used. The 8V battery packs offer a good balance between the range of the 6V battery and the acceleration capabilities of the 12V battery.

TYPES OF BATTERY FOR EVS

The following four types of batteries are commonly used today in EVs:

1. Lead Acid, 2. Nickel Cadmium (NiCd), 3. Nickel Metal Hydride (NiMH), and 4. Lithium-ion (Li-ion). Traditionally, most electric vehicles have used lead-acid batteries due to their mature technology, easy availability, and low cost. More recently, batteries using combinations of lithium ion and its variations are gaining widespread acceptance due to better efficiency, reduced weight, lower charging time, better power output, longer lifetime, and reduced environmental implications from battery disposal.

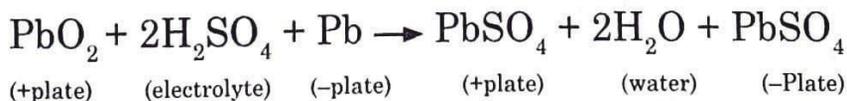
LEAD-ACID BATTERY

The first generation of EV batteries are likely to include advance lead-acid battery. Traditional liquid electrolyte lead-acid batteries have been used in many EV conversions, although they have numerous disadvantages for this application. Lead content has been reduced over time since they are heavy and have low energy densities, require frequent watering, generate gases when recharging and contain liquid electrolyte that can be hazardous if spilled in a collision. They have short life times (24000 to 40000 km) and they can be damaged if they are allowed to drain to too low charge often. Advanced lead-acid batteries are commercially developed and available.

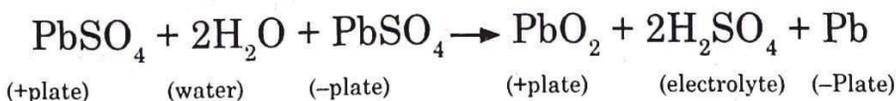
These batteries are lighter and maintenance free, have higher energy and power densities, can recharge much faster than conventional lead-acid batteries, and are sealed so that the gases generated during recharging recombine with chemicals in the batteries. However, they are expensive, highly toxic, and the amount cadmium reserves available to make these batteries may not be sufficient to supply a large demand in the EV market.

It is called lead-acid battery because its active ingredients are the metal lead and sulphuric acid. The difference in voltage between the positive plate (lead peroxide) and the negative plate (spongy lead) is 2.13 V when a sulphuric acid solution of 1.265 – 1.280 specific gravity is added, and the temperature is 68°F – 80°F. Lead peroxide and spongy lead are used in the automotive battery today because no other materials have a greater voltage difference.

(1) Chemical reaction when discharging



(2) Chemical reaction when charging



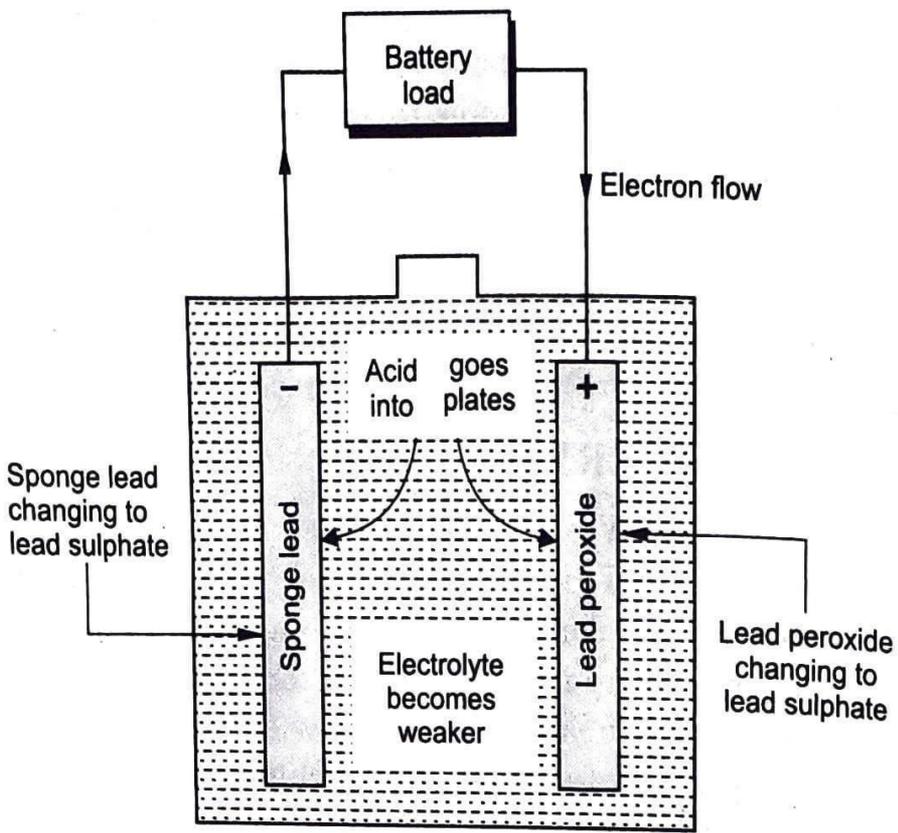


Fig.5.1: Discharging of a lead-acid battery

Discharge

During discharge, the lead peroxide (positive plate) and lead (negative plate) react with the electrolyte of sulphuric acid to create lead sulphate, water and energy.

Charge

During charging, the cycle is reversed: the lead sulphate and water are electro-chemically converted to lead, lead peroxide and sulphuric acid by an external electrical charging source.

Advantages

1. Reliable
2. Robust
3. Range
4. Rapid recharge
5. Tolerant to overcharging.
6. Low internal impedance.
7. Can deliver very high currents.
8. Ability to hold charge over a period of not being used
9. Indefinite shelf life if stored without electrolyte.
10. Can be left on trickle or float charge for prolonged periods.
11. Wide range of sizes and capacities available.

Disadvantages

1. Heavy and bulky.
2. Very low specific energy
3. Danger of overheating during charging
4. Not suitable for fast charging
5. Typical cycle life 300 to 500 cycles.
6. Must be stored in a charged state once the electrolyte has been introduced to avoid deterioration of the active chemicals.
7. Acid Fumes and corrosion - Results in decreased battery life
8. Loss of voltage over discharge.

LITHIUM-ION BATTERY

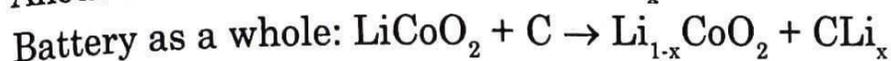
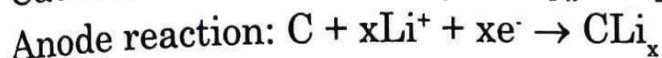
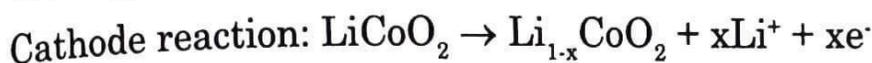
Lithium-ion batteries have higher specific energy relative to the other battery types. Advanced lithium batteries, including lithium-ion and lithium polymer batteries offer advantages of higher energy and power-densities with longer life on-board the vehicle as they can withstand over 1000 charge-discharge cycles. They are much lighter than lead-acid (three times or more the energy density of an equal weight) and promise a higher level of consumer safety, since lithium is non-toxic.

The use of lithium batteries in cars, motorcycles, heavy vehicles and off-road equipment is increasing rapidly.

Lead acid batteries are being replaced by lithium batteries to improve charge/discharge performance, save weight, save space, increase lifetime and avoid Pb (lead) in the environment.

This battery is now used primarily for electric vehicles, as they are much lighter which provides a more fuel efficient vehicle. The Porsche 911 2010 model uses the lithium ion battery for starting. These are very expensive batteries, and starting costs for cars are about Rs.60,000.

Charging reactions



Discharging reactions

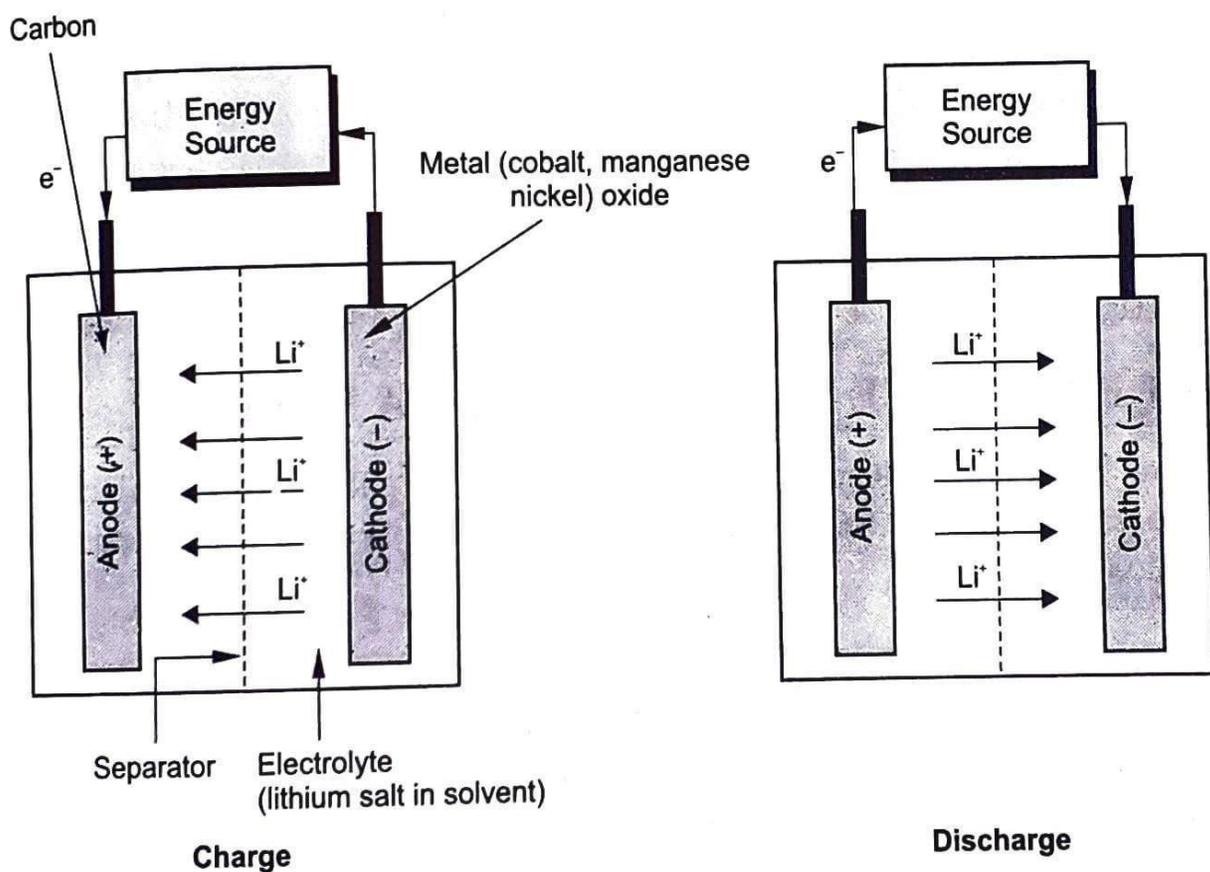
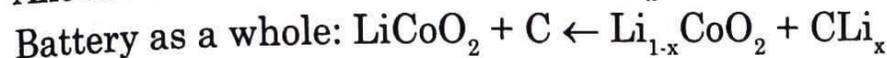
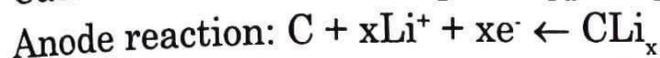
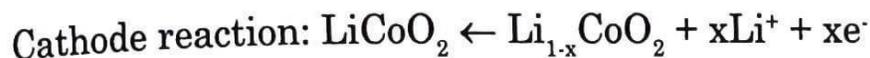


Fig.5.4: Lithium-ion battery

Lithium-ion cells, in their most common form, consist of a graphite anode, a lithium metal oxide cathode and an electrolyte of a lithium salt and an organic solvent. Lithium is a good choice for an electrochemical cell due to its large standard electrode potential (3.04 V) resulting in a high operating voltage (which helps both power and energy) and the fact that it is the metal with the lowest density (which reduces weight). In an automotive application a lithium-ion battery consists of tens to

thousands of individual cells packaged together to provide the required voltage, power and energy.

Advantages over conventional batteries

1. Higher specific energy
2. Higher specific power
3. Power to weight. Up to 80% weight saving
4. Charge and discharge at high currents
5. Low self-discharge
6. Offer phenomenal starting power and massive deep cycle reserve power. They are capable of providing engine cranking pulses of 2250 amps for 5 seconds.
7. Longer life span with a minimum of 5 years' service life, up to 10 years depending on use.
8. No harmful emissions
9. Loss of voltage over discharge

Disadvantages

1. Heat
2. Higher initial cost

ALTERNATIVE ENERGY STORAGE DEVICES

There have been various alternative energy storage devices including the flywheel and super capacitors. As a general rule both of these devices have high specific powers, which means that they can take in and give out energy very quickly. However, the amount of energy they can store is currently rather small. In other words, although they have a good power density, they have a poor energy density.

ULTRA CAPACITOR

Ultra capacitors, otherwise known as super capacitors or electrochemical capacitors, are different from batteries. Batteries store their energy chemically where an ultra capacitor stores it physically.

A capacitor is a device for storing electrical energy in a dielectric placed between two conducting plates. Small volume capacitors are used frequently in numerous types of electric circuits. Their capacity is directly proportional to the area of the conducting plates. Thus if large-area capacitors used, they gain a high storage potential. If the capacity per unit weight is the same or greater than the secondary battery it becomes possible to use it as an EV battery. Alternatively, using a material whose surface has numerous small holes in it would reduce the size of the capacitor.

In an electric car, an ultra capacitor can provide the power needed for acceleration, while a battery provides range and recharges the ultra capacitor between surges. Ultra capacitors can be charged and discharged much faster than batteries and are very suitable for storing the energy from regenerative braking, for climbing hills or sudden acceleration.

In China and many other places around the world now, super capacitors are being used as main power source for buses, where they are charged en route at intervals in just about 30 seconds. Use in buses, trams and trains is increasing.

Principle

The double-layer capacitor technology is the major approach to achieve the ultra capacitor concept. The basic principle of a double-layer capacitor is illustrated in Fig. 5.5. When a voltage is applied across the electrodes, a double layer is formed by the dipole orientation and alignment of electrolyte molecules over the entire surface of the electrodes.

By adopting high-dielectric materials, short separation distances and large electrode surface areas, the capacitance can be greatly increased. At the present status of ultra capacitor technology, the corresponding electrode materials may be carbon/metal fibre composites, doped conducting polymer films on carbon cloth or mixed metal oxide coatings on metal foil, while the electrolyte materials may be aqueous/organic solution or solid polymer.

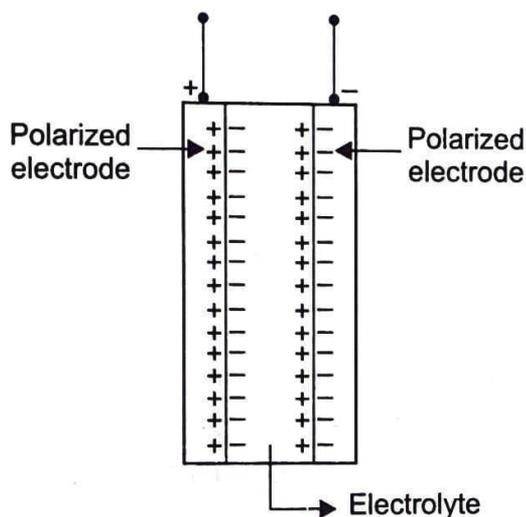


Fig.5.5: *Basic principle of ultracapacitors*

Characteristics of ultracapacitors

Capacitors have a number of great properties. They store power as electrical charge rather than chemical energy. This typically allows near instant charge times and very high peak output currents. They can survive hundreds of thousands of charge-discharge cycles, rather than the hundreds of cycles for full-cycled batteries. Ultracapacitors have little or no internal resistance (down to 0,12 m Ω), allowing them to work at close to 100% efficiency.

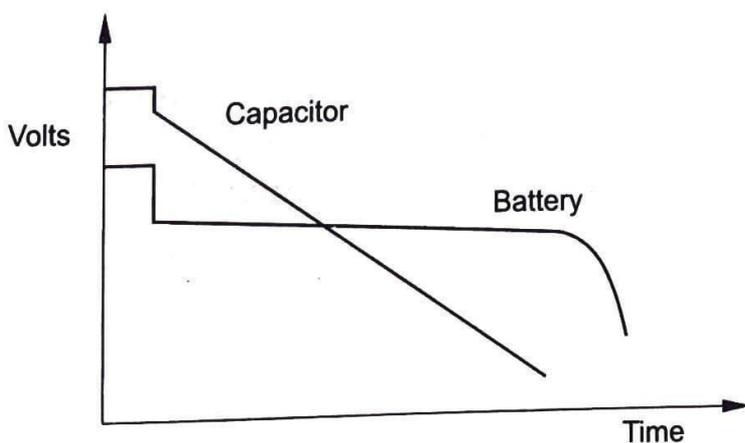


Fig.5.6: *Performance of ultracapacitor*

A battery's voltage stays nearly constant as it discharges at a constant current. Thus the power output is nearly constant. A capacitor's voltage drops linearly over time at a constant current. Thus,

power output drops linearly. In order to use the capacitor as a battery replacement, voltage regulation circuit is required that can step up voltage as it drops, which means a linear increase in current output is needed to deliver a constant power output.

The other problem is that modern ultracapacitors have much lower specific energy than batteries.

The ultracapacitor has 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 5 kW/kg, much higher than any type of battery. Due to their low specific energy density and the dependence of voltage on the state-of-charge, it is difficult to use ultracapacitors alone as an energy storage for EVs and HEVs.

Supercapacitors do not go anywhere near the energy density of batteries today at current status of development. So they cannot run car over long distances like batteries. However they are used in modern cars, both EVs and hybrid vehicles in combination with batteries, to extend life of batteries and take over number of functions of batteries, and get better performance in the process. Ultracapacitor technology is ideally suited to regenerative braking and start-stop systems. Start-stop applications enable an engine to shut down when it comes to a stop at a red light, or when sitting in traffic. Ultracapacitors then provide a short burst of energy that restarts the motor.

Ultracapacitors are good partners for lithium-ion batteries and other high-energy-density storage technologies. The two can be connected in parallel to create combined power supply units. Due to load leveling, ultracapacitors can significantly expand battery life and improve safety.

The power density of ultracapacitors is up to 60 times greater than batteries. This high power density means it's possible to recharge large banks of ultracapacitors in just three or four seconds. This means they are ideally suited for applications that require high bursts of power.

Advantages

1. Can store 10 to 100 times more energy per unit volume or unit mass than standard electrolytic capacitors.
2. Can be charged and discharged more quickly (almost instantly) than batteries.
3. Tolerate many more charge/discharge cycles than rechargeable batteries.

4. Able to provide large surges of power in short periods of time without overheating.
5. Deliver many times more power for weight than lithium-ion batteries.
6. They have efficiencies of up to 98%.
7. Unlimited cycle life (over 1 million cycles).
8. Tolerant of high temperatures.
9. One of the cheapest technologies available for power discharges below 15 secs.

Disadvantages

1. Only about 1/10 the energy density of batteries (and thus are physically larger for a given amount of energy).
2. Low maximum voltage.
3. Extremely high capital cost.

FLYWHEEL

The flywheel is an energy storage device, similar to a battery, but instead of storing the energy chemically, it is stored in kinetic form in a rotating disc. Typically, the rotor is accelerated by an electric motor (charging process) and decelerated when the motor is switched to generative operation (discharging).

This flywheel energy storage system (FESS) composed of composite rotors spinning at thousands of rpm on frictionless magnetic bearings, which can drive a generator to provide power for EVs. Energy stored in flywheels increases quadratically with rotational speed of the rotors. As energy is used up, the rotor slows. American Flywheel Systems developed a first generation EV flywheel. This company claimed that the flywheel is of the same size as the 6-volt battery, but weighs much less, stores 3 times the energy and lasts ten times longer. Gyroscopic effect is avoided by having two adjoining wheels counter rotating at identical speeds on a stationary shaft. Friction is reduced to negligible levels by suspending the wheels in vacuum. The company speculates that the range would be extended to 300 miles on a single charge in relation to that of lead-acid battery. The life of the flywheel would, theoretically be very long and no replacement would be needed relative to the chemical battery systems.

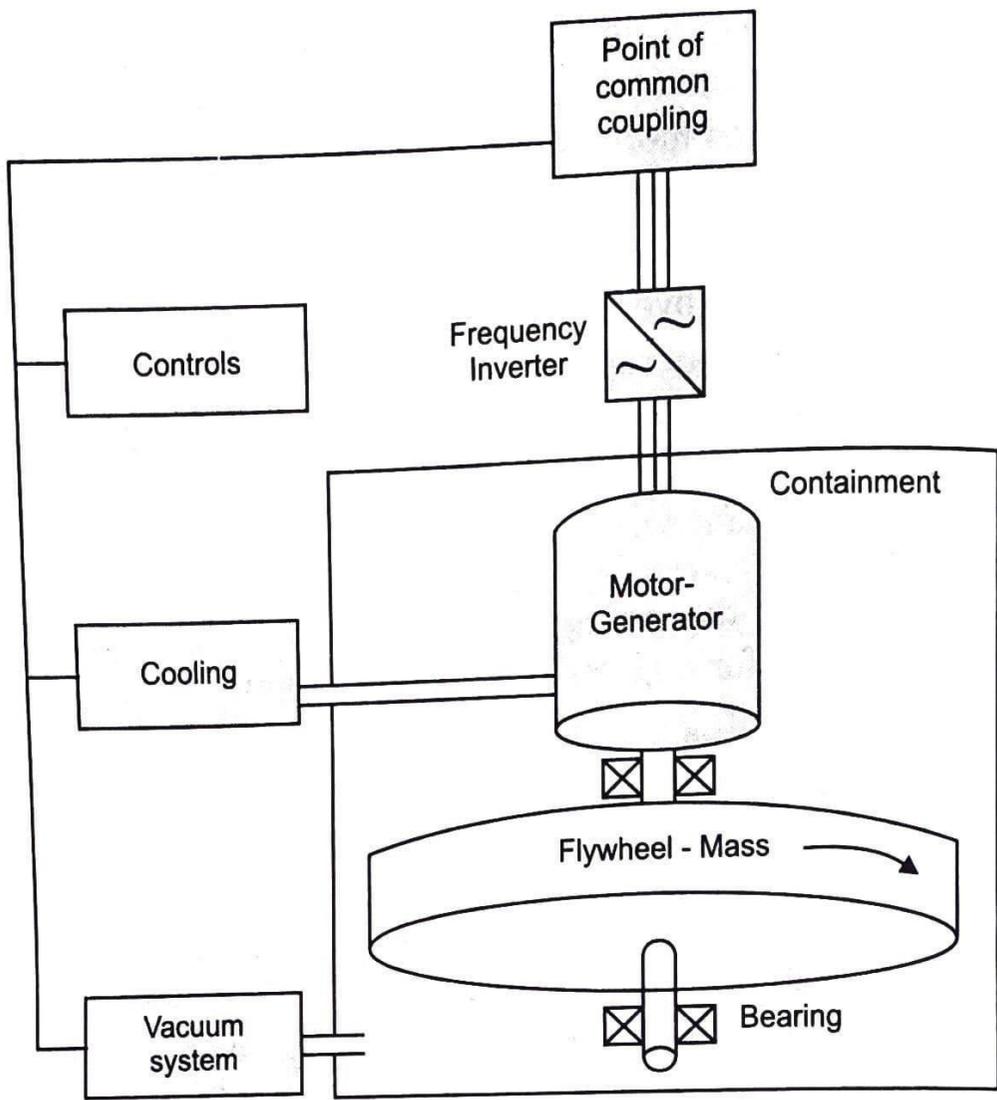


Fig.5.7: Flywheel energy storage system

The importance of energy storage with flywheel is to reduce the loss of mechanical energy, namely the loss of kinetic energy that consists of air friction resistance and rotary resistance. According to different means for the reduction of energy loss, FESS can be divided into low-speed flywheel system and high-speed flywheel system. The first reduces air friction by increasing the mass of flywheel while the second is to reduce the air pressure of operating environment of flywheel. The high-speed flywheel system benefits from the use of high strength compound material (carbonic fibre). It has characteristics of small mass, low volume and high speed. Thus it is fit for vehicle usage.

The high-speed flywheel system consists mainly of a flywheel, a motor and a generator. It is connected with exterior electrical systems through input or output electronic equipments and the power transported from exterior systems is converted from electric energy into mechanical energy by raising rotary speed of flywheel. When it is needed to output power, mechanical energy is converted back into electric energy through generator and meantime the rotary speed of flywheel is reduced. The motor and generator are usually integrated together and magnetic suspension bearings are adopted by flywheel

system, through the support of which the flywheel is fixed in a vacuum container.

Advantages

There are primarily four properties that make the flywheel attractive for use as energy storage:

1. High power density
2. Long cycle life
3. No degradation over time
4. Easily estimated state-of-charge
5. Highest energy storage density
6. Shortest charging time
7. Easiest maintenance
8. No pollution

Disadvantages

Excessive high cost. Its cost is about 1.5 times that of ultra-capacitor and is about 6 ~ 7 times that of chemical battery.

Comparison between battery, ultracapacitor and flywheel

	Battery	Ultracapacitor	Flywheel
Storage mechanism	Chemical	Electric	Mechanical
Life	3-5 Years	1-18 Years	> 20 Years
Temperature range	Limited	Limited	Less limited
Relative mass (Equivalent energy)	Large	Middle	Small
Time to hold a charge	Months	Days	Hours

Electric Motor

Electric motors convert electrical energy into mechanical energy. Two types of electric motors are used in electric vehicles to provide power to the wheels: the direct current (DC) motor and the alternating current (AC) motor.

DC motors are larger and more complicated than AC motors, and it is difficult to make them highly efficient. On the benefit side, however, is that the DC motor's controller can be easily made. As a result, most of the EVs use DC motors. The features of the AC motor are just the opposite. Advances of semiconductor field can be used to make the DC-AC inverter for the AC motor's controller highly efficient and small in size. The combination of motor and controller is making the AC motor gradually superior in terms of the efficiency, price and size.

However, with the advent of better and less expensive electronics, a large number of today's electric vehicles are using AC motor/controller systems because of their improved motor efficiency and lighter weight.

Requirements of EV motor

The major requirements of the EV motor drive are summarized as follows:

1. High instant power and high power density
2. High torque at low speeds for starting and climbing as well as high speed at low torques for cruising
3. Very wide speed range including constant-torque and constant-power regions
4. Fast torque response
5. High efficiency over wide speed and torque ranges
6. High efficiency for regenerative braking
7. High reliability and robustness for various vehicle operating conditions
8. Reasonable cost.

BRUSHED DC MOTOR

The simplest motor that can be used in automotive applications is the brushed DC motor. This motor is used in all sorts of domestic electric appliances like hairdryers and fans. In Fig.6.1 a two-pole brushed DC motor is shown with one coil. The motor consists of a stator with two permanent magnets and brushes and a rotor (coil) with commutator and windings.

The force on the left side is upwards where the force on the right side is downwards, causing the coil to turn clockwise. When the wires of the coil with the commutator are clear of the magnets momentum carries the rotor halfway around until it connects with the brushes again. The commutator is constantly changing the direction of the current to assure that the forces are pushing the coil clockwise.

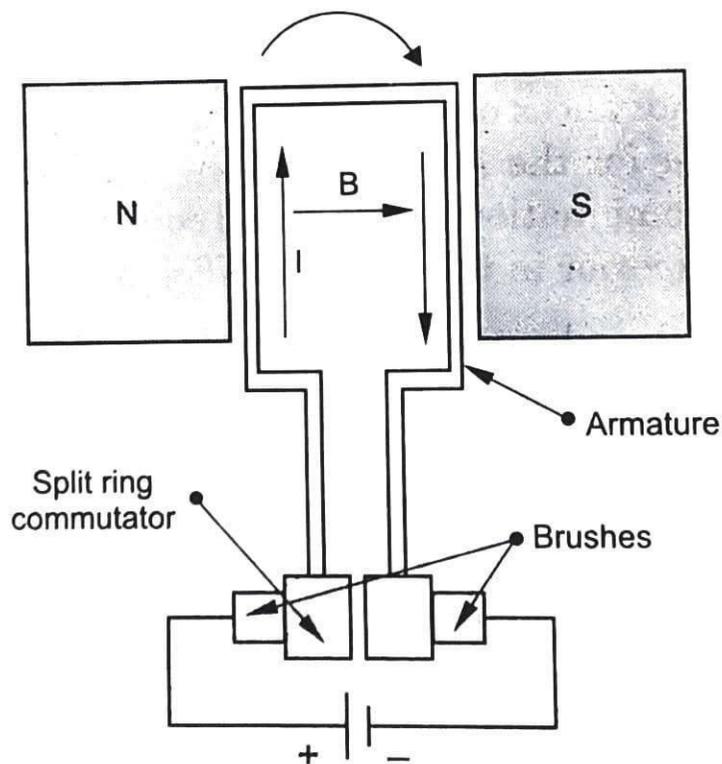


Fig.6.1: Brushed DC motor

A real DC motor however is using a rotor with multiple coils and a stator with more than one pair of magnets but the principle remains the same.

There are three basic brushed DC motors; a parallel, series and separately excited brushed DC motor as shown in Fig.6.2 For use in electric vehicles the one that can be used is the separately excited motor. The required torque can be controlled at any angular speed giving the motor great flexibility.

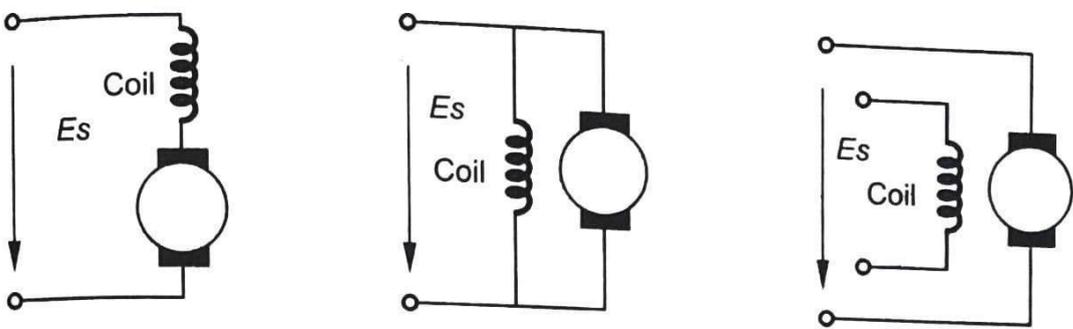


Fig.6.2: Basic brushed DC motors

Due to the brushes making physical contact with the commutator, sparking is a common issue with brushed motors. They are causing friction, limit the speed range and need regular maintenance.

BRUSHLESS DC MOTOR

A brushless DC (BLDC) motor actually is not a DC but an AC motor. The motor needs an alternating current but must have variable frequency. Therefore the current have to be derived from a DC power supply. The BLDC motor is given different names by manufacturers and users of which the most common are permanent magnet synchronous motor (PM synchronous), self-synchronous AC motor, variable frequency synchronous motor and electronically commutated motor (ECM).

The motor has a three-phase stator with a number of coils and a rotor with surface mounted permanent magnets. The stator and the rotor are reversed compared to the brushed DC motor where the permanent magnet are mounted on the stator.

U : Phase-U winding
 V : Phase-V winding
 W : Phase-W winding
 Rotor : Magnet

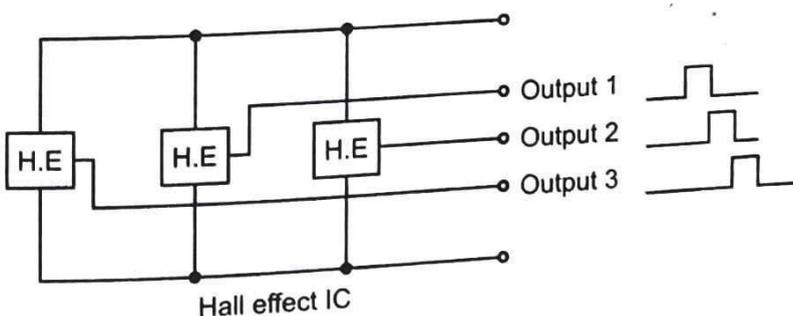
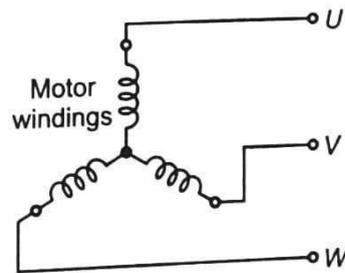
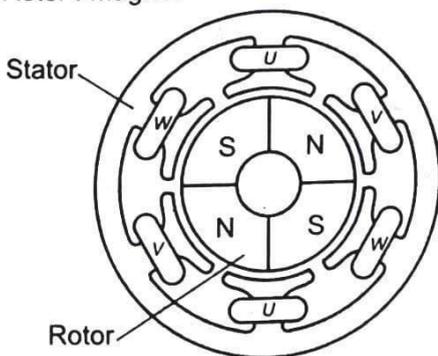


Fig.6.3: Brushless DC motor

The way a BLDC motor works is that the poles on the stator are alternating, in such a way that the rotor is turning clockwise. The pole on the stator pulls the pole on the rotor clockwise and when the poles are in line with each other the current is switched off. Momentum then carries the rotor further and the current is reversed, changing the magnetic field and the poles in the stator. To make sure the motor keeps on turning sensors are needed to determine the position of the rotor. This is often done using Hall Effect sensors.

BLDC motors are very efficient. Torque is high under low speeds and goes down as the speed goes up. A drawback of this type of motor is the price compared to the other possible EV motors. A BLDC motor needs a strong permanent magnet that can influence the total price of the motor.

SWITCHED RELUCTANCE MOTOR

The switched reluctance (SR) motor is a simple motor with an iron rotor and stator. The stator is magnetised and attracts the rotor. When the rotor is aligned with the stator (magnetic field is symmetrical) the current is switched off and momentum carries the rotor further and the current is switched on again.

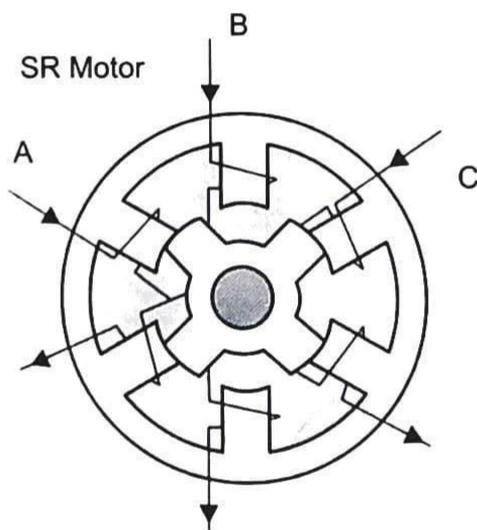


Fig.6.4: Switched reluctance motor

The stator and control electronics of a SR motor are similar to those of a BLDC and induction motor. The rotor of a SR motor however is much simpler, making it cheaper and more rugged than the BLDC and induction rotor. The SR motor does not create back EMF because it has no permanent magnets. It therefore can reach higher speeds. Back EMF is the voltage that is generated when an electric motor with permanent magnets is spinning. The speed of a BLDC motor is limited because of this back EMF.

Also the current in the coil of a SR motor does not need to alternate. It needs an advanced control systems and sensors to adjust the speed

and make sure the current is switched on and off on time. Another drawback of the motor is that it is a bit noisy. SR motors are not used in commercial EVs and HEVs yet, but because of the good properties and possible low costs of the motor they will become more widespread in the future.

AC INDUCTION MOTOR

Instead of using a permanent magnet in the rotor (as in the BLDC motor), it is also possible to induce a current in the rotor to create a temporary magnet. This is done in an AC induction motor. The rotor type that is most common in an Induction Motor (IM) is the 'squirrel cage'. The rotor consists of a stack of steel laminations with evenly spaced conductor bars around the shaft. The conductor bars are forming a kind of cage. The conductor bars are electronically linked with end rings.

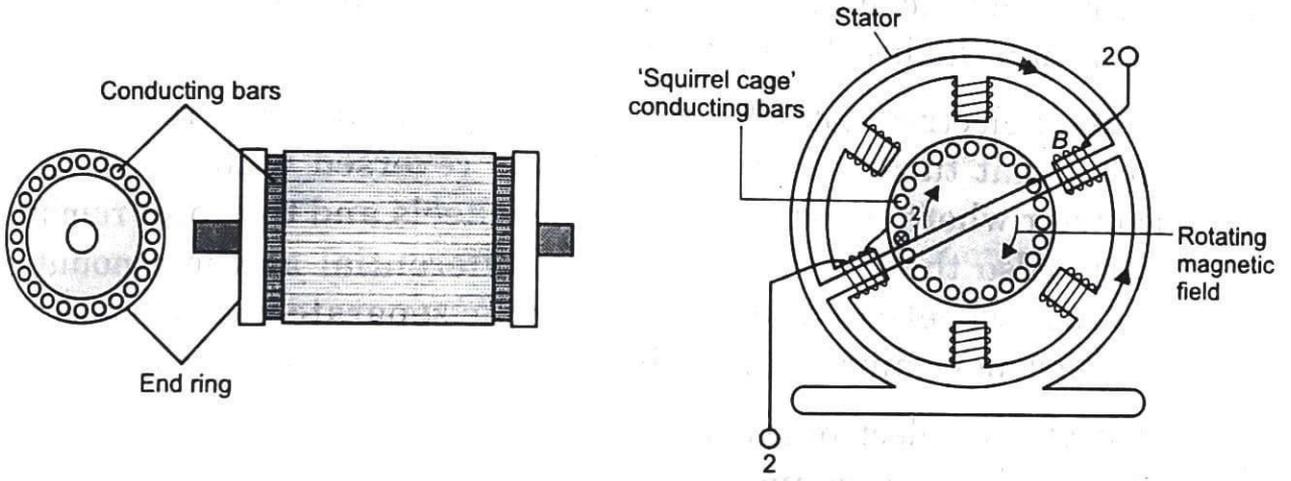


Fig.6.5: AC induction motor

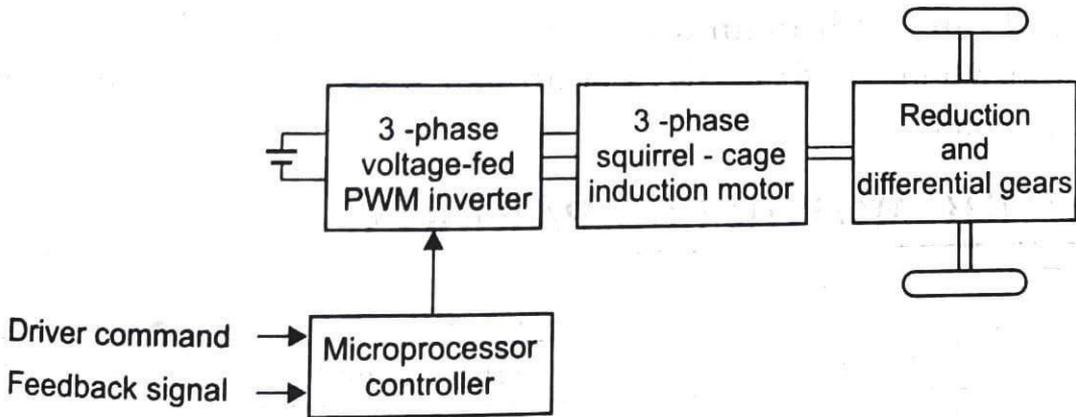


Fig.6.6: Basic EV induction motor drive configuration

The rotor of an IM consists of a number of coils with the windings displaced by 120° . When a 3-phase AC is supplied to the rotor a current is induced in the conductor bars of the rotor. It will turn clockwise 'chasing' the magnetic field that is going anti-clockwise. The angular speed of the rotor is lower than the magnetic field. This so called 'slip' velocity is the relative velocity between the rotor speed and magnetic field.

The technology of the IM is very mature and is used in all sorts of appliances like washing machines, pumps and industrial machines. Therefore it is a popular choice and most used in EVs and HEVs of today.

The Think city electric vehicle and the Tesla Roadster which are already on the market uses a 3-phase AC induction motor. BEVs that are coming onto the market next years also uses other electric motors. The Mitsubishi iMiev for example (in Europe known as the Peugeot iOn) and the E6 from BYD are equipped with a BLDC motor or Permanent Magnet Synchronous Motor as the car manufacturers names the motor.

IN-WHEEL MOTOR VERSUS CENTRAL MOTOR

The BEVs that are on the market (for example the Tesla Roadster and Think City) are equipped with a central electric AC induction motor. The central electric motor is cheaper to produce and is also more developed than the in-wheel electric motor.

A central electric motor has a stationary stator and a rotor with a differential that turns the wheels. This is reversed with an in-wheel electric motor where the stator turns the wheels and the rotor remains stationary. Also there is no need for a differential as the amount of power to each wheel can be controlled by the separate in-wheel electric motors. Efficiency gains can be achieved with this type of motor.

However the electronics of an in-wheel motor have to be well developed as the precise amount of energy has to be delivered to each wheel. At this moment there are some safety issues as malfunction of one wheel can result in an uncontrollable vehicle. At this moment it is uncertain when the first BEVs equipped with in-wheel motors will be on the market.

ELECTRIC MOTOR COMPARISON

AC motor	DC motor
Single-speed transmission	Multi-speed transmission
Light weight	Heavier at equivalent power
Less expensive	More expensive
95% Efficiency at full load	85-95% Efficiency at full load
More expensive controller	Simple controller
Motor/controller/inverter more expensive	Motor/controller less expensive

Motor type	Advantages	Disadvantages
Brushed DC motor	<ul style="list-style-type: none"> Low initial cost Simple speed control 	<ul style="list-style-type: none"> High maintenance (brushes) Low lifespan High heat
Brushless DC motor	<ul style="list-style-type: none"> Long life span Least rotor heat generated Low maintenance High peak efficiency High efficiency at lower load conditions Reliable 	<ul style="list-style-type: none"> High initial cost Requires a controller Poor high speed capability Non-adjustable magnetic field
Switched reluctance motor	<ul style="list-style-type: none"> Low initial cost High average efficiency Highly reliable and robust Very simple control 	<ul style="list-style-type: none"> High acoustic noise Requires large filter capacitor Failure of one leg phase does not interfere operation of remaining leg phases
Induction motor	<ul style="list-style-type: none"> Low initial cost High power High average efficiency Light weight Small volume Mature technology 	<ul style="list-style-type: none"> Rotation slips from frequency Accumulation of rotor heat

Indian Electric Vehicles

India is well suited for the introduction of EVs today with the existing technologies available, making EVs cost effective. EVs with a top speed of 40-60 kmph and a range of 50-60 km would meet over 90 percent of the city mobility requirements in India. The average daily driving distance for the metropolitan area in India is 35 kilometers, which is well within the range of typical electric cars.

The current market for EVs is very small in India. Though there are different types of E2Ws (scooters and bikes), E4Ws (electric cars), and electric buses, the overall share of EVs is negligible.

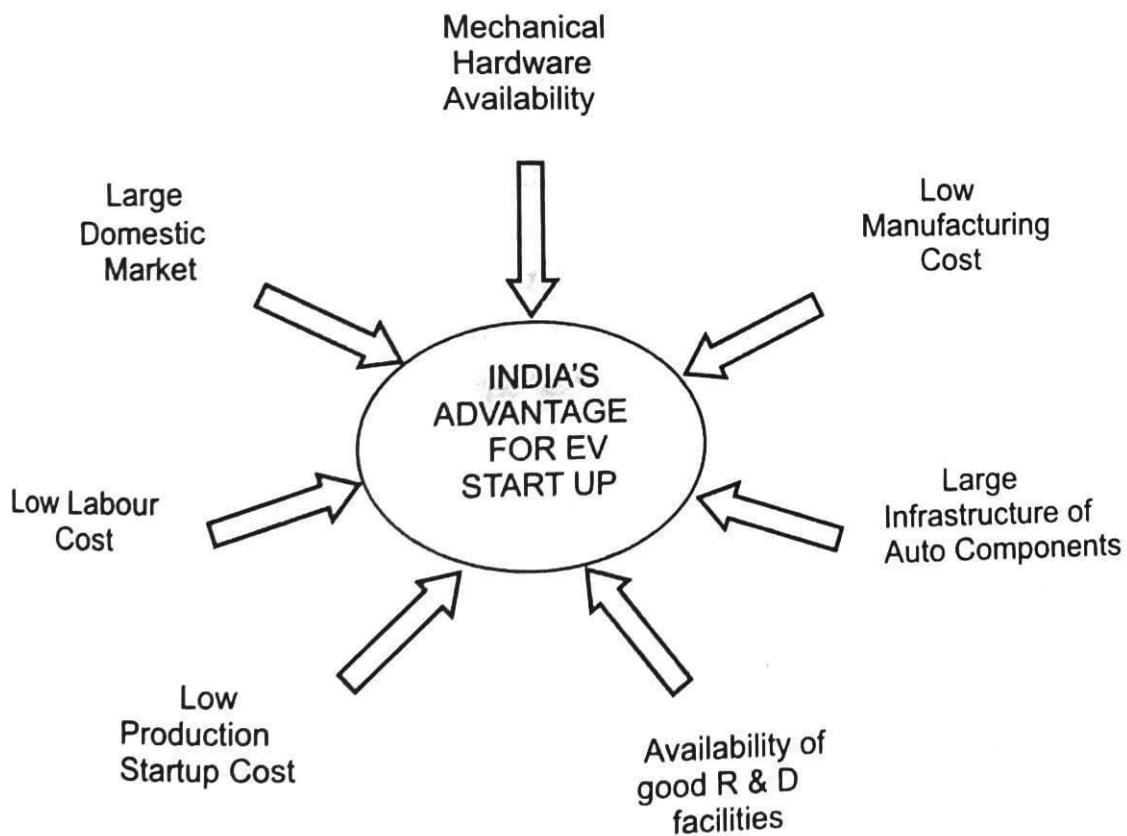


Fig.11.1: India's advantages for EV start up

India stands out for its mechanical hardware availability and low manufacturing cost. Other advantages for India are its low labour cost, low production start up cost, availability of R & D facilities in electrical, electronics and auto industries coupled with large infrastructure of auto components, less present investment in internal combustion engine capacity and the potential of large domestic markets.

Information technology and electronics facilities further enhance its EV manufacturing potential. With the largest EV potential market in the world, the chance of reducing the production of EV costs in the near future is highest in India.

4-WHEELERS



REVA

The first electric car in India was launched by Bangalore based company REVA in early 2000s. Reva is a stylish, fully automatic (no clutch-no gears), compact two-door hatch back that carries two adults and two children or a payload of 227 kg. It has a top speed of 65 km/h and a range of 80 km. In view of traffic congestion, narrow roads and inadequate infrastructure characteristic of our Indian cities, the average driving speeds maintained during city driving are below 30 km/h. EVs like Reva are ideal for these conditions. A small turning radius of just 3.5 m makes it easy to park and maneuvers in difficult city traffic conditions.

Reva has an onboard charger to facilitate charging by plugging into a 220V, 15 amp socket at home or at work place. The auto cut-off mechanism prevents overcharging. The charge time is 5-6 hours though 80% of the full charge can be attained in 2.5 hours, good enough for 65 km. A full charge consumes just about 9 units of electricity. This elegant, light yet rugged, two-door hatch back offers the safety and convenience of a 4-wheeler at the operating cost of a 2-wheeler.

Mahindra electric

Mahindra Electric Mobility Limited, formerly known as the Reva Electric Car Company, involved in designing and manufacturing of compact electric vehicles. Mahindra Electric started their journey in to the EV space in 2011 by launching Mahindra Reva, India's first electric car. They subsequently launched Mahindra E20, the current version on roads in India. Powered with lithium ion batteries, the new model

allows for a top speed of 80 km/hr and a driving range of 100 km with a single charge. With a charging time of 5 hours, it is marketed to provide significant cost savings over a conventional car.

Company	Brand	Battery type
Mahindra	e20	Li-ion
	e-Verito	Li-ion
TATA	Indica Vista Electric	Li-ion

Tata motors

Tata motors have launched a car-Tigor EV and have recently delivered their first set of cars to Energy Efficiency Services Ltd from their Senand Plant in Gujarat. The Tigor Electric will be able to do about 120-150 kilometers on a full battery charge.

The Nano EV could be the first electric car that the automaker launches in India, followed by the Tigor and Tiago electric vehicles. Electric car charging infrastructure is at its infancy in India, and the government is fast stepping up its efforts to roll out charging stations.

Tata Motors is setting up 400 charging stations in Delhi alone and has plans for more cities. They plan to develop their own vendor for chargers as well.

3-WHEELERS



More recently, electric rickshaws are gaining popularity as a good substitute for conventional three-wheelers (rickshaws) and paddle-rickshaws as public and goods transportation over short-to-medium distances. Scooters India Ltd and Mahindra & Mahindra Ltd have brought out battery operated three wheelers, which are already running in several cities in India. Bajaj, TVS and Ashok Leyland are working on hybrid and pure electric EVs.

In Delhi alone there are more than 100,000 e-rickshaws. e-rickshaws must be registered and the drivers are required to have driving licenses. The challenges for using e-rickshaws are:

1. Use of lead-acid batteries, which need to be replaced within 7-8 months.
2. Current design of e-rickshaws does not possess the required vehicle strength and often fail on safety standards.
3. Unavailability of fixed e-rickshaws stands and charging points.

2-WHEELERS



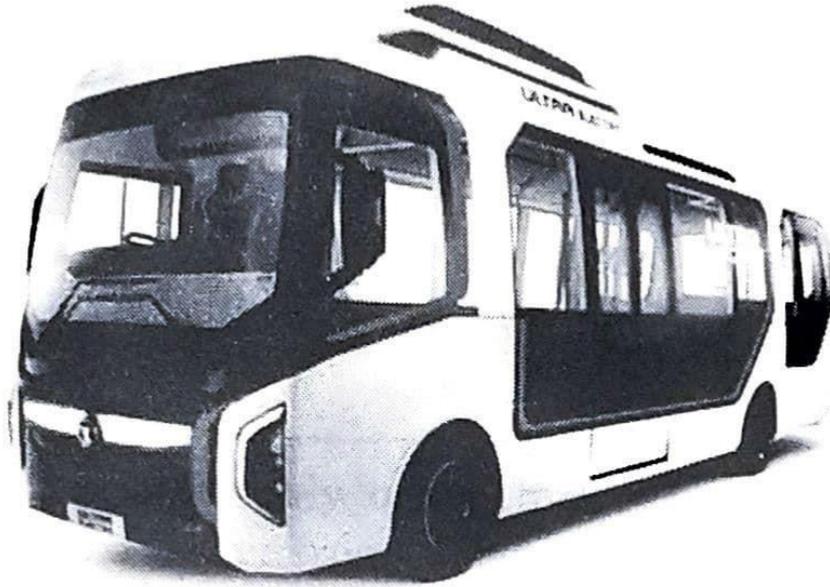
2-Wheeler is the largest segment in the Indian automotive industry representing ~80% of Indian automotive sales. Around the year 2000, only a couple of electric two-wheelers were available in the Indian market. However, the market has expanded and over two dozen different two-wheelers are available in the market at present. These include low speed vehicles with a maximum speed of 25 km/hr to high speed vehicles capable of achieving speeds up to 65 km/hr. The driving range varies from 20 km to 100 km.

The following aspects would help drive e-mobility in this segment:

- Over 2 million petrol-run delivery bikes with a long daily run engaged in courier and food delivery services.
- Intra-city travels (maximum of around 100-150 km a day)
- Ease of charging: Can be easily charged on a standard residential/workplace plug point.

	e-Bike	Petrol run Bike
Range, km	70 – 120	300 – 450
Price, Rs	90,000 – 1,25,000	75,000 – 1,20,000

ELECTRIC BUS



The Bangalore Municipal Transport Corporation has recently introduced an electric bus on a dense corridor in the city.

Intra-city buses are likely to be electrified early, driven by the support provided by government-run transport undertakings, route predictability and ease of charging at bus depots. SCVs and LCVs are likely to be early adopters in the truck segment.

E-TRUCKS



The demand for fuel-efficient trucks is expected to increase further with India's plan to leapfrog to BS-VI emission norms in 2020. This could provide a thrust toward the adoption of electric trucks in India as ICE trucks are likely to get costlier by up to 20%, leading to a convergence in prices of diesel-powered and e-trucks.

Hybrid Vehicles

HYBRID VEHICLES

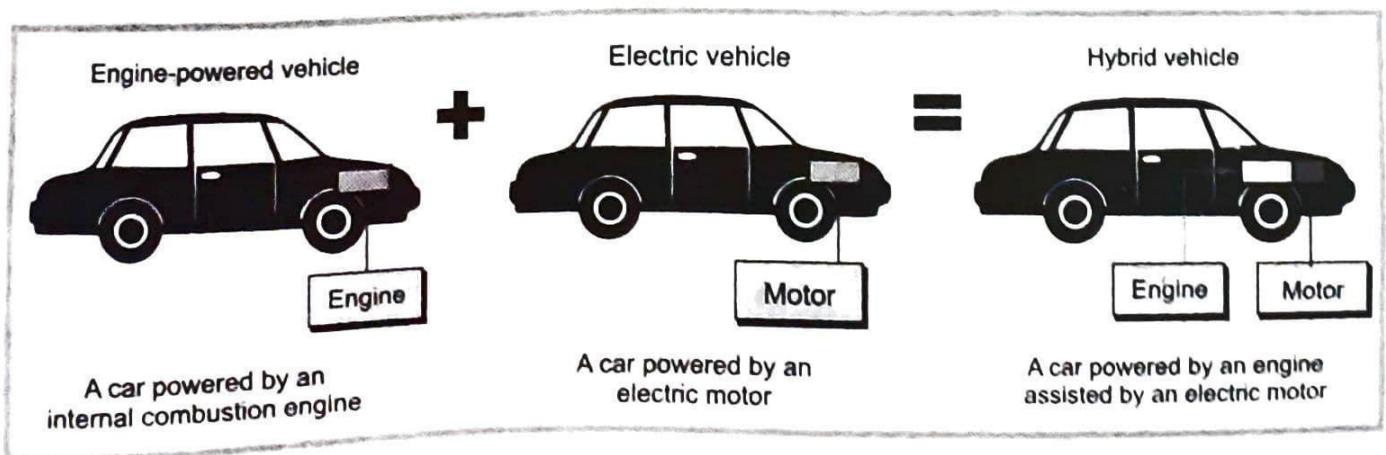
Pure electric vehicles run only on batteries and need a charger to replenish the battery's power from an electrical outlet.

A hybrid is a vehicle that has two or more power sources to propel it. An example that is often seen is a moped. The petrol engine is one power source and the rider provides the second power source by 'pedal power'. Other vehicles that are classed as hybrid include some trains (diesel and electric) and submarines (nuclear and electric).

HYBRID ELECTRIC VEHICLES (HEV)

A hybrid electric vehicle (HEV) is a type of vehicle that uses both an electric motor (s) and a conventional internal combustion engine (petrol or diesel engine). This type of vehicle is considered to have better performance (increased torque and power), fuel economy and reduced emissions compared to a conventional one of the same size, performance and comfort.

Hybrid vehicle has a small battery (shown in red color) which drives the vehicle over a short distance before switching to engine. A hybrid electric vehicle cannot be plugged in for charging. Instead, the battery is charged through regenerative braking and by the internal combustion engine.



Hybrid electric vehicles (HEVs) incorporate a small internal combustion engine with an electric motor and storage batteries. They

eliminate the basic weaknesses of electric vehicles (limited range, bulky and heavy, more time for recharge, etc) and internal combustion engines (harmful emissions, higher fuel consumption, etc).

A hybrid electric vehicle has more promise than an electric vehicle, since the HEV has an internal combustion engine to provide the energy to meet vehicle range requirements. The battery then provides the additional power needed for acceleration and climbing hills. The fuels used in the HEV engines in current production include gasoline, diesel and natural gas.

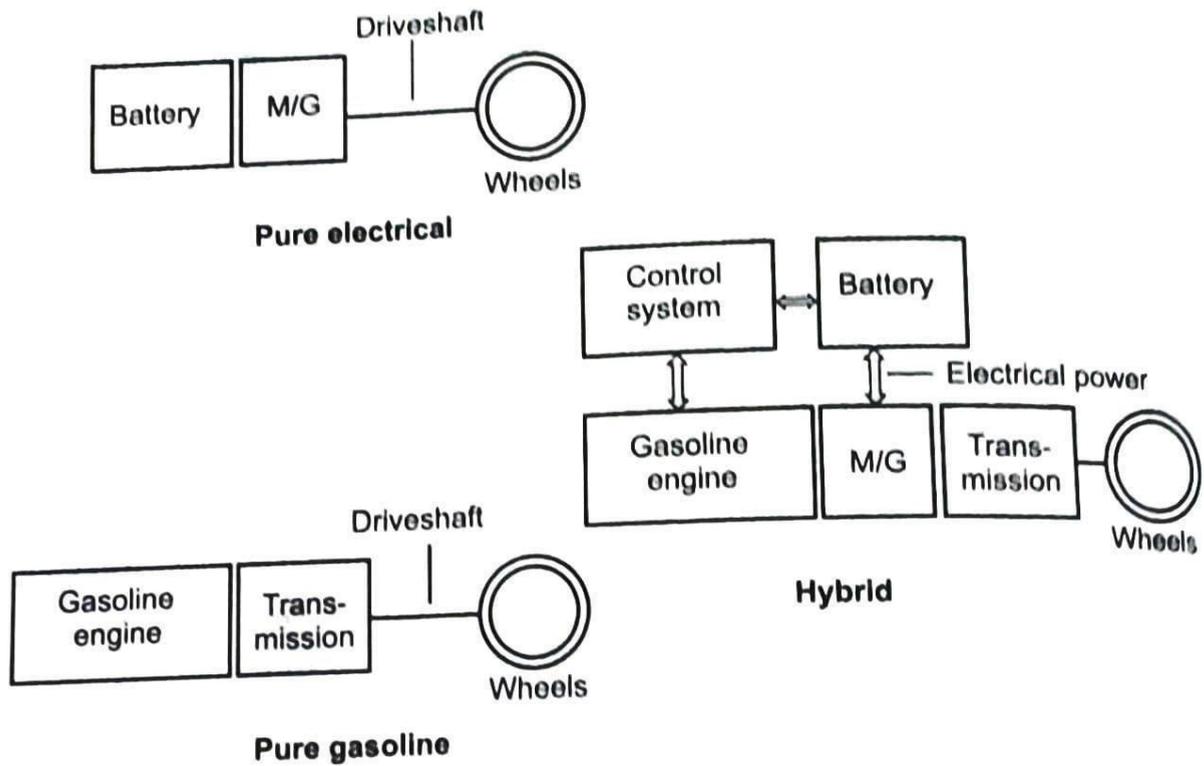


Fig.12.1: Concept of Hybrid Electric Vehicle

Internal combustion (IC) engines produce dangerous emissions and have poor efficiency at part load. IC engine cars are both lightweight and can cover extensive distances before they need to refill the fuel tank. Refilling the fuel tank is very rapid compared with the time taken to recharge batteries. The disadvantages of the IC engines are high emissions and high fuel consumption when compared to electric power. Electric drives produce 'no' emissions but have a limited range. The solution is to combine the best aspects of both IC engine and electric drives.

A hybrid car combines the low emissions and low fuel consumption of an electric vehicle and provides a lightweight vehicle that can travel a long distance. Depending on how the hybrid system is designed, the engine simply functions as a means of driving a generator. The generator then charges the batteries that power the electric motors, which provide power to the vehicle transmission.

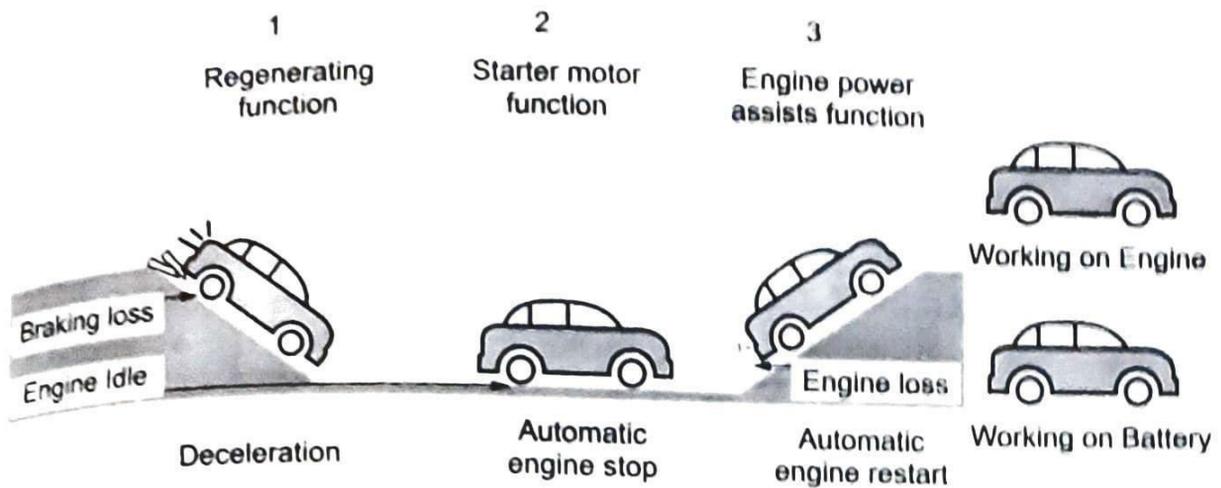


Fig.12.2: Working of HEVs

This type of vehicle can use the electric drive in slow traffic and towns, and use the IC engine on the high way. An efficient control system allows even better usage such that under certain conditions both the motor and the engine can be used.

HEVs usually have the following properties:

Auto-start/auto-shutdown - To avoid wasting energy during idle time, the engine of a hybrid electric vehicle automatically shuts down and starts as soon as the accelerator is touched.

Regenerative braking - Considered one of the salient features of HEVs, the energy wasted during braking and coasting is converted and stored in the battery, which is then used by the electric motor.

Electric motor assist - By helping the engine during passing, accelerating or moving up a hill, the electric motor allows the engine to be made smaller and more efficient in nature.

Advantages

1. Low exhaust emission levels.
2. Longer range than BEV.
3. Engines can be down sized to accommodate average load, not peak load, which reduces the engine's weight.
4. Fuel efficiency is greatly increased.
5. Low maintenance cost

Disadvantages

1. Bulky and heavy.
2. Require very complicated control systems.
3. Still produces emissions
4. Expensive to operate (8-10 times more expensive than BEV) but less than traditional gasoline vehicle.
5. No ability to conveniently charge at home.

COMPONENTS OF HYBRID ELECTRIC VEHICLE

A typical hybrid car contains the following components.

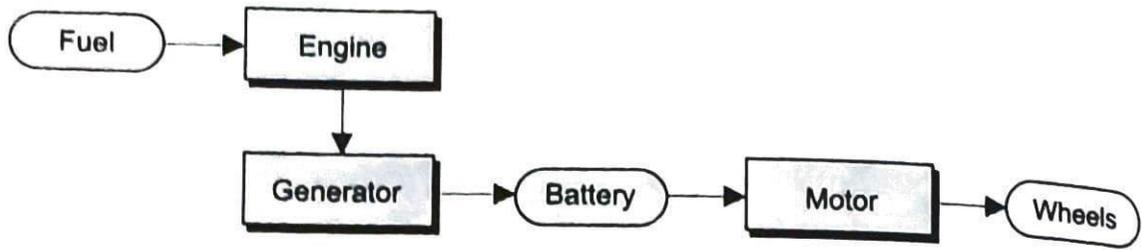


Fig.12.3: Components of HEVs

Petrol engine

The engine is similar to those fitted to conventional vehicles e.g. four cylinders, four-stroke normally aspirated, etc. However, the capacity of the engine used is relatively small. These engines are lightweight and very fuel efficient. They typically produce approximately 70 brake horsepower which is supplemented with a electric motor rated typically at approximately 50 horse power.

Electric motor

The electric motor is used to propel the car, however with the use of electronic technology, the motor can also function as a generator to recharge the batteries.

Electric generator

Electric generator generates electricity from the rotating wheels while braking, transferring that energy back to the traction battery pack. Some vehicles use motor generators that perform both the drive and regeneration functions.

Controller

Regardless of the energy source, an electric vehicle needs a controller, which is connected to the accelerator pedal, for directing the flow of electricity from the energy source to the motor.

DC/DC converter

This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.

Transmission

The transmission transfers mechanical power from the engine and/or electric traction motor to drive the wheels. The transmission can be either manual or automatic.

Fuel tank

The fuel tank is used to store petrol for the petrol engine.

Batteries

The batteries provide the energy source for the electric motor, either recharged by an external power source or recharged by the generator or electric motor when it is functioning as a generator. Most electric cars use lead-acid batteries, but new types of batteries, including zinc-chlorine, nickel metal-hydride and sodium-sulphur, are becoming more common.

Battery (auxiliary)

In an electric drive vehicle, the auxiliary battery provides electricity to start the car before the traction battery is engaged and also powers vehicle accessories.

Traction battery pack

Traction battery pack stores electricity for use by the electric traction motor.

WORKING OF HYBRID VEHICLES

Figs.12.4-12.7 show the energy flows in a basic HEV.

Starting

While starting the vehicle, the IC engine may run the motor as a generator to produce some power and store it in the battery.

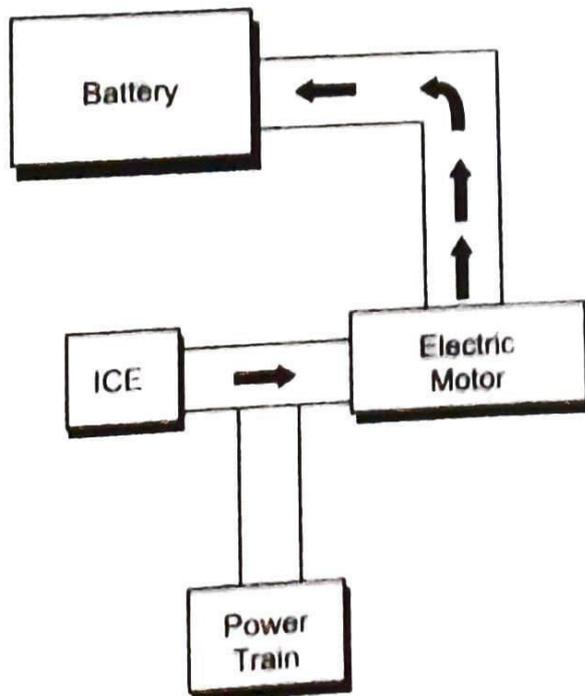


Fig.12.4: Starting

Passing

Passing needs a boost in speed, therefore the IC engine and the motor both drives the power train.

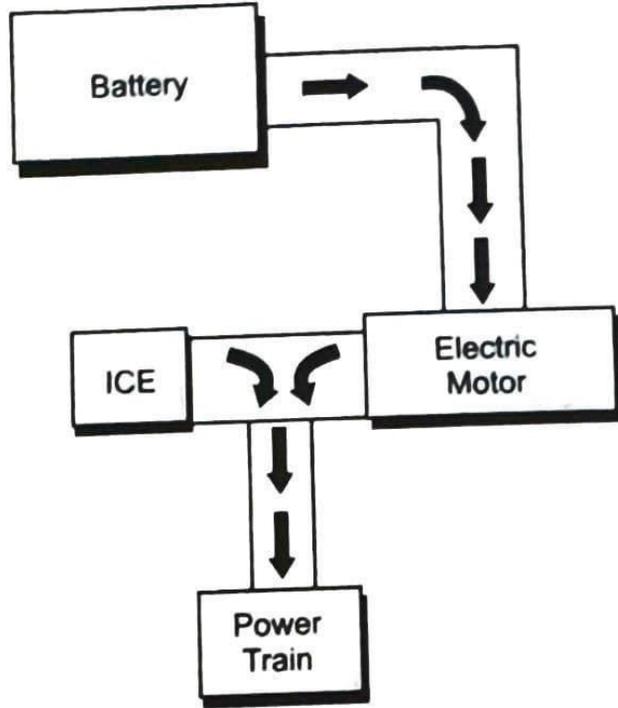


Fig.12.5: *Passing*

Braking

During braking the power train runs the motor as generator to charge the battery by regenerative braking.

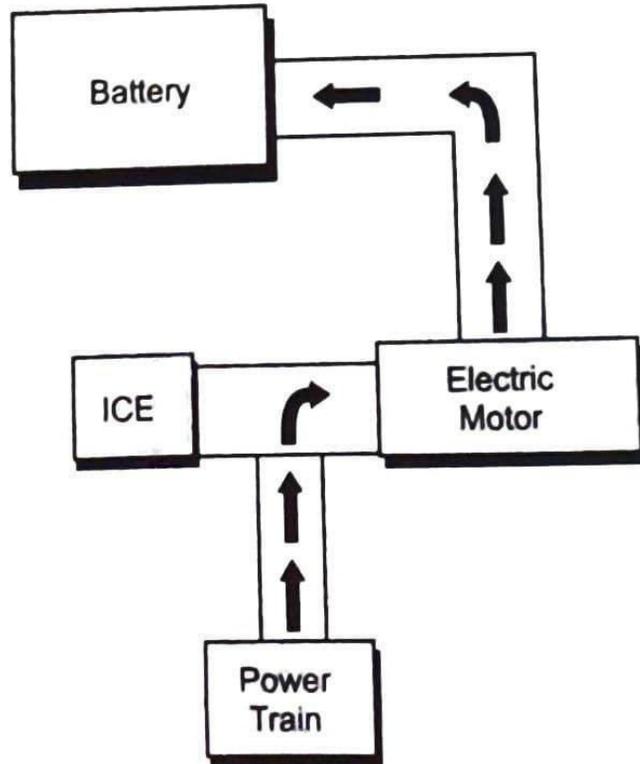


Fig.12.6: *Braking*

Cruising

While cruising, IC engine runs both the vehicle and the motor as generator, which charges the battery. The power flow is stopped once the vehicle stops.

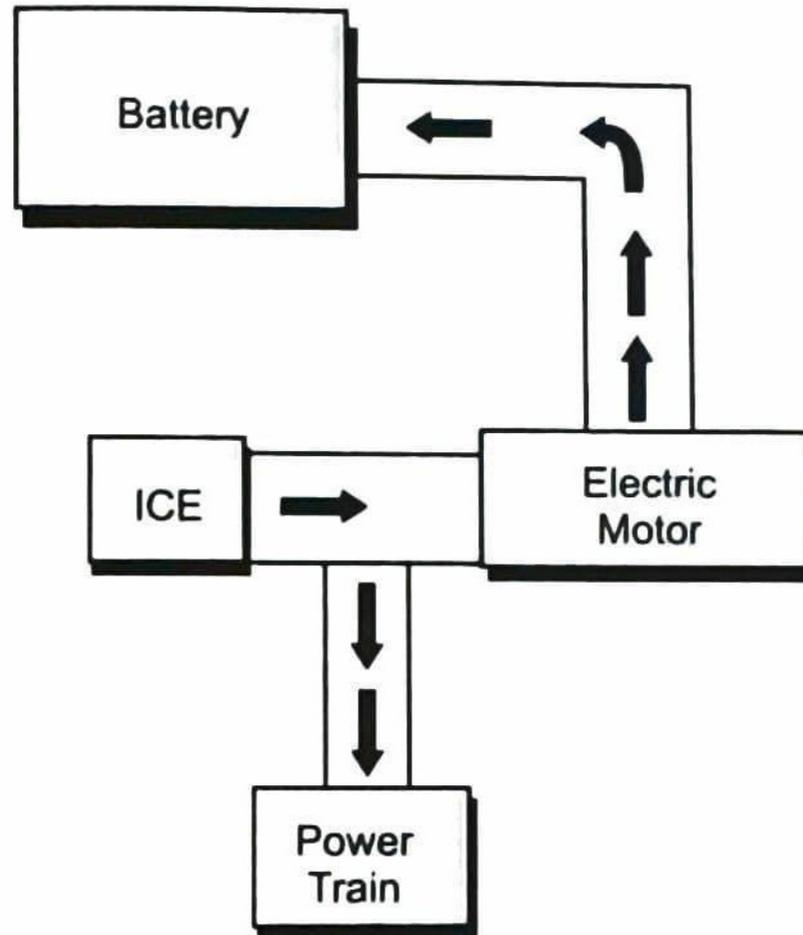


Fig.12.7: Cruising

Hybridisation

Hybrid cars are most commonly classified in the following 3 categories:

1. Micro hybrid
2. Mild hybrid
3. Full hybrid

MICRO HYBRID

Micro hybrid technology is the lowest level of vehicle hybridisation. It contains mainly start-stop technology. Here, energy stored in an auxiliary battery is used to quickly start a vehicle at the traffic signal.

In this system the starter and the alternator are replaced with an electrical machine. The internal combustion engine switched off when the vehicle stops. When the vehicle sets off again it is quietly accelerated to idle speed by the electrical machine, and then the ignition is activated.

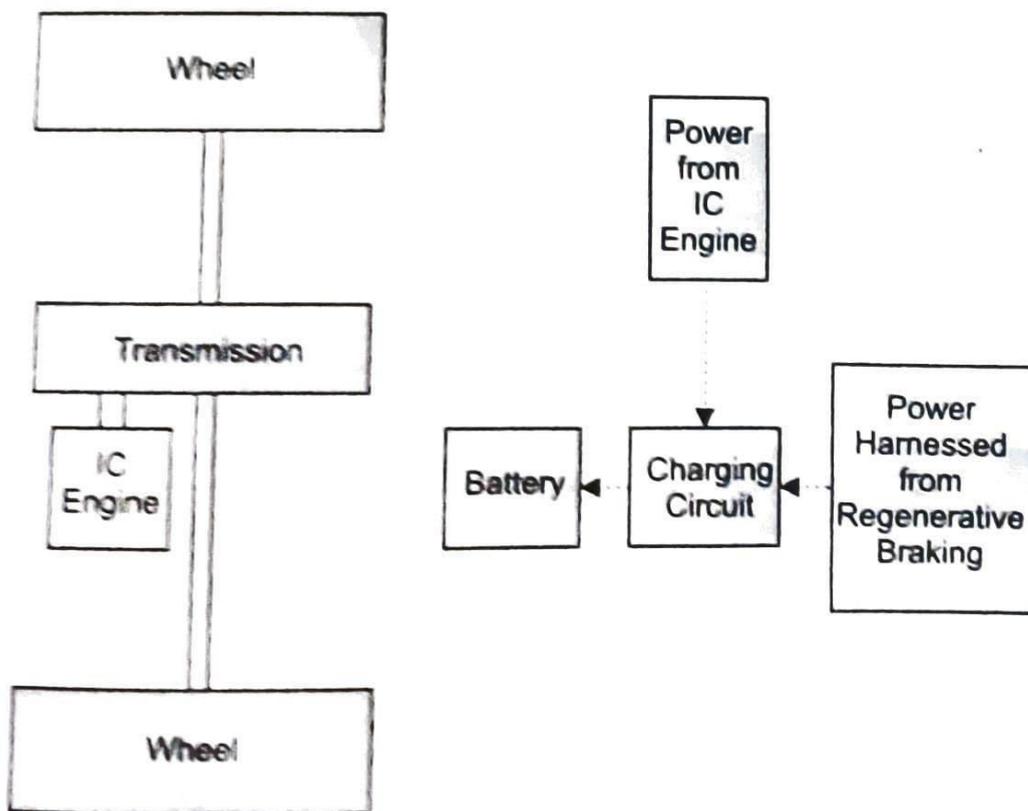


Fig.13.1: Block diagram of a micro hybrid.

Advantages

1. Fuel consumption is reduced from 5 to 10% in city driving.
2. CO₂ emission is reduced.

3. Engine restarts in milliseconds.
4. Noise and vibrations are suppressed.
5. Implementation cost is not very high.

Disadvantages

1. High maintenance cost
2. Some vehicle functions (air conditioner, etc) may not run when engine is off.

Application

In India, a common example of micro hybrid is the Mahindra Scorpio. Tata motors introduced this technique in Tata ACE. BMW, Fiat, Honda, Volkswagon and many other automobile manufacturers use this technology.

MILD HYBRID

The next level of hybridisation is the mild hybrid where electrical energy is used for start-stop and also for driving vehicle for short distance at low speed or to aid in acceleration. A mild hybrid's motor is only able to assist the engine; it is not potent enough to drive the car independently, hence the word 'mild'.

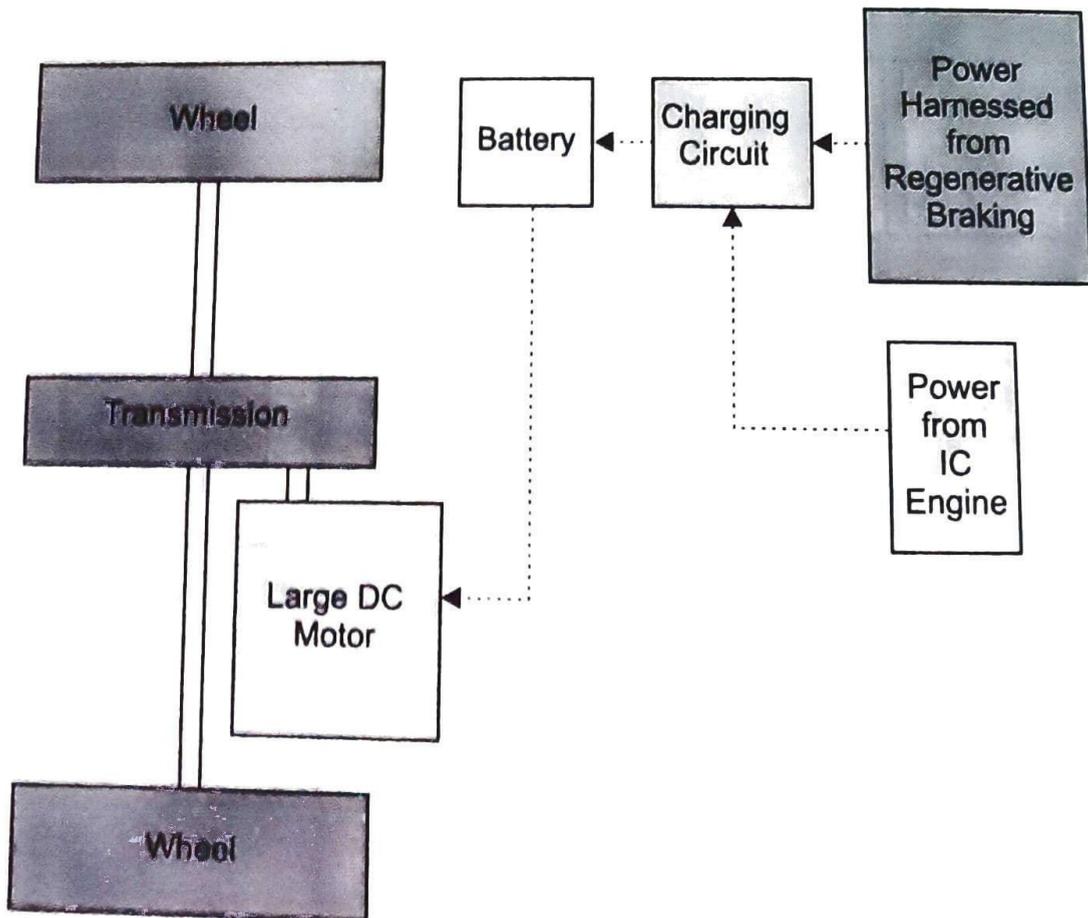


Fig.13.2: Block diagram of a series mild hybrid

Mild hybrid cars spend most of their time powered by their combustion engine, with a small motor/generator usually taking the place of a conventional alternator—the device that normally charges the battery in a regular combustion-engined car. The electric motor can be directly flanged to the crankshaft in a mild hybrid. In mild hybrids, additional electrical energy of up to 20 kW is provided by the electric traction accumulator (battery). Unlike a full hybrid system the electric motor of a mild-hybrid system never propels the car on its own, with the motor/generator only delivering power for starting off and accelerating at low engine rpm.

As well as providing a boost to the engine, mild hybrids cut the ignition when engine power isn't needed such as when stationary, rolling or when braking – a system more commonly known as engine start-stop. Some also capture energy using regenerative braking, which converts the car's kinetic energy when decelerating and stores it as electrical energy in the batteries.

Advantages

1. Improve efficiency by up to 15%
2. Weight savings
3. Smoother starting

Disadvantages

1. Not able to run on electric power alone.
2. Higher CO₂ emissions than conventional hybrids

Applications

Honda Insight, Honda CR-Z.

TYPES OF MILD HYBRID

Mild hybrid is of two types:

- Parallel
- Series

Parallel mild hybrid

A small DC motor (Starter/generator) is coupled in parallel with the main IC engine. The additional DC motor provides assistance to the IC engine as and when required. The DC motor makes use of the battery which utilized the regenerative braking system power for charging. It also uses intelligent stop-start system. It cannot power the vehicle with DC motor alone.

Example: General motors parallel hybrid truck

Series mild hybrid

Here a large DC motor is coupled directly with the wheels. The motor is charged by an IC engine with additional support from the power harnessed from the other sources. It also uses intelligent stop-start system. Here the vehicle can be run by the DC motor alone.

Example: Chevy Malibu

FULL HYBRID

A full hybrid (HEV), sometimes also called a strong hybrid, is driven over longer distances with the electric drive alone. The internal combustion engine does not function during electric driving. As strong hybrids can travel considerable distance using electrical energy only, zero emissions can be achieved. The accumulator of these systems is more powerful than those of the above-mentioned micro-hybrid and mild-hybrid variants. The voltage of the traction electrical system or the battery usually ranges between 200 and 350V. It has a typical output of about 25 to 50 kW.

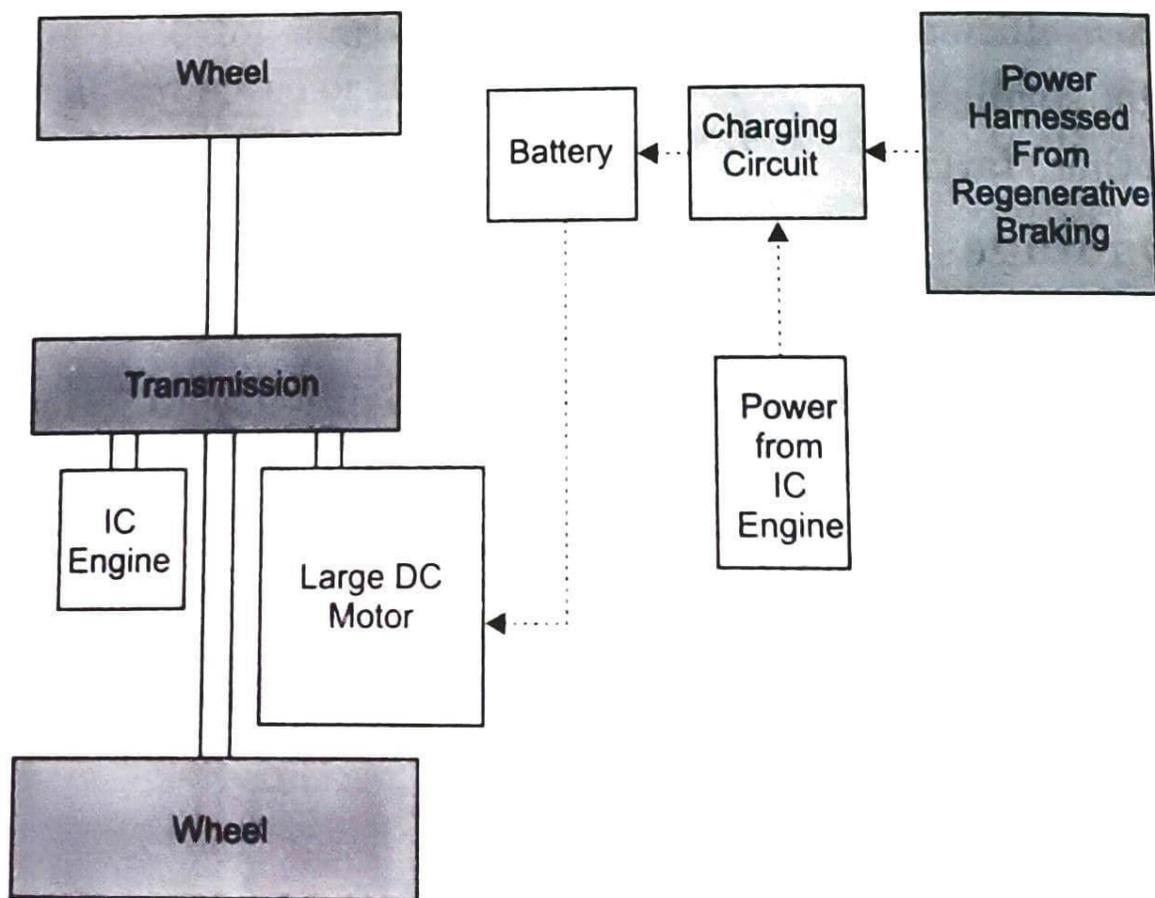


Fig.13.3: Block diagram of a full hybrid

The full hybrid can be classified as a parallel hybrid or a series hybrid. The fuel savings of a full hybrid can be up to 30%.

Example: Lexus CT200h

Fuel Cell Electric Vehicle (FCEV)

The feasible alternatives to batteries for electric vehicles and hybrid electric vehicles are fuel cells and flywheels.

Fuel cell

A fuel cell is an electrochemical energy conversion device. A fuel cell converts the chemicals hydrogen and oxygen into water and in the process it produces electricity (DC voltage) with water and heat as its by-product. In principle, a fuel cell operates like a battery. Unlike battery, a fuel cell does not run down or require recharging. It will produce electricity as long as fuel is supplied.

There are different types of fuel cells, each using a different chemistry. Fuel cells are usually classified by the type of electrolyte they use.

- Alkaline fuel cell
- Phosphoric fuel cell
- Solid oxide fuel cell
- Molten carbonate fuel cell

Principle

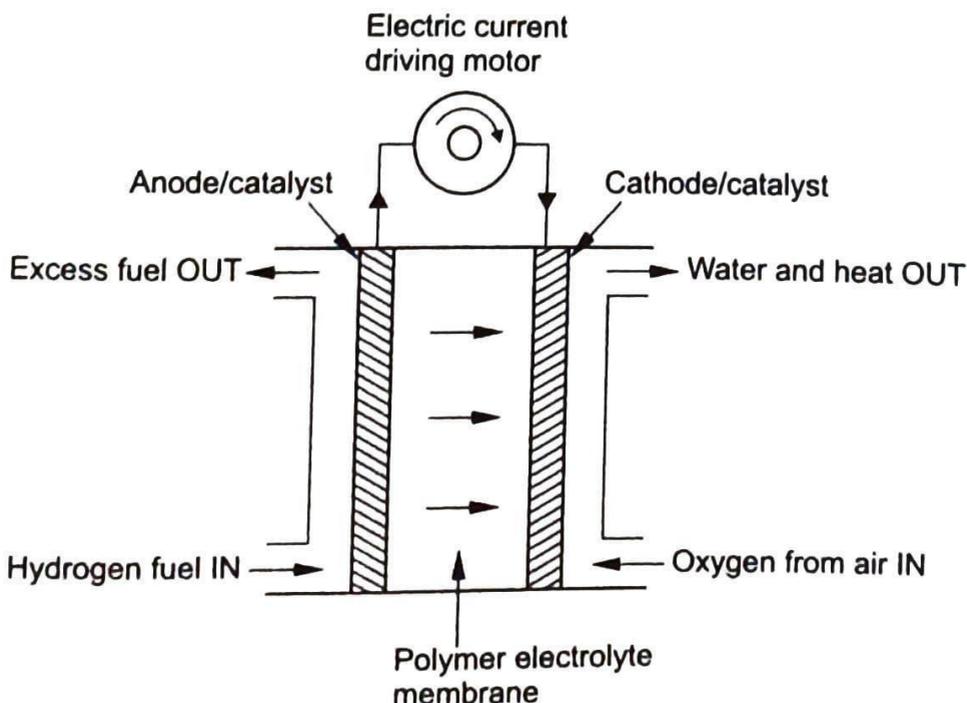


Fig.16.1: Fuel cell

A fuel cell consists of two electrodes sandwiched around an electrolyte. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat.

The pressurised hydrogen gas (H_2) entering the fuel cell on the anode side, which is negative post of the fuel cell. It conducts the electrons that are free from the hydrogen molecules so that they can be used in an external circuit. It has channels etched into it that disperse the hydrogen gas equally over the surface of the catalyst.

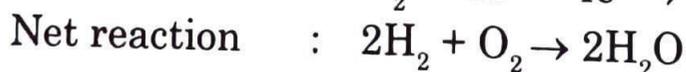
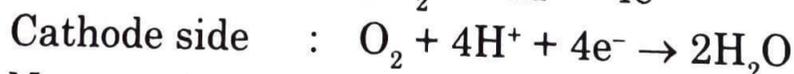
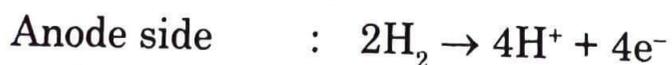
Oxygen (or air) enters through the cathode, which is the positive post of fuel cell. The cathode also has channels etched into it that distribute the oxygen to the surface of the catalyst. It also conducts the electrons back from the external circuit to the catalyst where they can combine with the hydrogen ions and oxygen to form water.

The electrolyte is the proton exchange membrane. This specially treated material only conducts positively charged ions. The membrane blocks electrons.

The catalyst is a special material that facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so that the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum-coated side of the catalyst faces the Polymer Electrolyte Membrane (PEM).

Working principle

The pressurised hydrogen gas (H_2) entering the fuel cell on the anode side. This gas is forced through the catalyst by the pressure. When a hydrogen molecule comes in contact with the platinum on the catalyst, it splits into two H^+ ions and two electrons (e^-). The electrons are conducted through the anode, where they make their way through the external circuit (doing useful work such as turning a motor) and return to the cathode side of the fuel cell.



Meanwhile, on the cathode side of the fuel cell, oxygen gas (O_2) is being forced through the catalyst, where it forms two oxygen atoms. Each of these atoms has a strong negative charge. This negative charge attracts the two H^+ ions through the membrane, where they combine with an oxygen atom and two of the electrons from the external circuit to form water.

This reaction in a single fuel cell produces only about 0.7 Volts. To get this voltage up to a reasonable level, many separate fuel cells must be combined to form a fuel-cell stack.

Advantages

1. There are no emissions from the vehicle
2. Noise levels are very low
3. Vehicle is vibration free
4. Operating range is comparable to conventional vehicles
5. Highly efficient

Disadvantages

1. Storage and handling with some primary fuels such as hydrogen and natural gas is difficult
2. It is difficult to match the electrical output to fluctuating vehicle demand
3. Complicated controls are needed

1.3 Vehicle Emission Control Technologies

The advances in engine design, air–fuel mixture preparation, and proper ignition timing can considerably reduce emissions in modern ICE vehicles. However, these advances often do not meet increasingly stringent emission policies and regulations. An obstacle towards further improving the release of vehicle emissions is the conflicting specifications of engine complexity, fuel efficiency, power, and emission requirements. As such, emission control technologies are important in normalizing engine emissions to standard levels without jeopardizing vehicle and engine performance.

Emission control systems are designed to reduce the amount of air pollution emitted by a vehicle. Types of tank-to-wheel emissions of ICE vehicles are tailpipe exhaust emissions, evaporative emissions, and crankcase emissions. Tailpipe exhaust emissions refer to emissions that are expelled into the air through the exhaust pipe. These emissions usually contain hydrocarbons, carbon monoxide, nitrogen oxide, and particulate matter. Evaporative emissions refer to fuel vapors that escape into the air through the fuel tank or during refueling. Likewise, crankcase emissions are unburned or partially burned fuels vented to the engine compartment.

Gasoline and diesel engines use several technologies to control emissions, with the most important ones being catalytic converters, exhaust gas recirculation, crankcase emission control, and evaporate emission control. While the structures may differ, the main functions of these control technologies are similar for both engine types [16–21].

1.3.1 Advanced Engine Design

Emissions from an ICE can be reduced by improving the engine design and controlling the combustion process. Engine design should be optimized for efficiency and performance under a variety of driving conditions, while minimizing its emissions. Properly controlling the engine and combustion process variables such as ignition timing, air–fuel ratio, the volumetric efficiency, and the compression ratio can also significantly reduce the level of engine emissions. Advanced control technologies such as fuel injection systems, electronic engine units, controlled air induction systems, variable valve timing, and turbocharging systems have been shown to be effective in reducing emissions of both diesel and gasoline vehicles. Generally, the most important of these are variable valve timing and turbocharging systems. The subsequent section discusses these two technologies in detail.

1.3.1.1 Variable Valve Timing

“Valve timing” is the time interval within which a valve is open, while the time interval in which the intake and exhaust valves simultaneously open is called a “valve overlap time” or

“timing of breathing.” Proper controls of valve timing and valve overlaps play an important role in reducing engine emissions, improving engine fuel economy, and enhancing the output power. For example, a slight delay in the closing of the intake valve pushes some air–fuel mixture back into the intake manifold by the piston during the compression stroke. This action subsequently increases the intake manifold pressure and results in a richer air–fuel mixture during the next cycle. What this sequence of events means is that delayed intake valve closing results in better fuel economy and lower nitrogen oxide emissions during partial load conditions. However, these benefits come at the expense of a slight loss in peak engine torque. In contrast, closing the intake valve earlier during normal combustion circumstances produces lower pressure within the cylinder during the compression stroke. Consequently, this reduces the amount of work required from the piston. The early intake valve closing also produces better fuel economy and lower nitrogen–oxide emissions. However, closing the intake valve earlier also increases hydrocarbon emissions due to low temperatures caused by low-pressure conditions. Another disadvantage of prematurely closing the intake valve is the reduction in engine performance at high-speed conditions. Engine performance suffers under these circumstances because the intake valve closes before the maximum amount of air–fuel mixture enters the cylinder.

In general, reductions in overlap result in a smoother idle and more slow-speed torque, while increases in overlap produce more power and better engine breathing. However, the disadvantages of more overlap include rough idling and high exhaust emissions. Most conventional vehicles use an engine with fixed valve events, in which valves open and close at fixed times during engine strokes, independent of engine load and speed conditions. The flexibility of variation in valve events that are subject to speed and load conditions allows the engine to operate more efficiently over its operating range and conditions.

The design of variable valve timing aims to improve engine performance by controlling the timing of valves through different operating modes. This technology makes it possible to control the stream flow of intake and exhaust gases coming into and out of the combustion chamber with variable valve events. It also allows the engine to achieve optimal power and torque across a wider range of engine speeds with lower emissions. In diesel engines, the combination of variable valve timing and exhaust gas recirculation can significantly reduce the hydrocarbon and nitrogen–oxide emissions. However, this reduction comes at the expense of an increased amount of particulate matter in the exhaust.

1.3.1.2 Turbocharging Systems

The primary function of a turbocharger is to increase the amount of oxygen inhaled into the combustion chamber by compressing the air intake. This compression results in enhanced volumetric efficiency, reduced particulate matter and hydrocarbon emissions, and improvements in fuel efficiency. However, due to the increase in combustion pressure, turbochargers can also increase the rate of nitrogen–oxide emissions. A turbocharger is composed of a turbine, a compressor, and a center housing/hub rotating assembly (see Figure 1.8). Hot exhaust gases drive the turbine and they leave the engine through the exhaust ports. The captured kinetic energy of the exhaust gases drives the compressor through a shaft in the turbo housing. The blades of the compressor draw ambient air inside and accelerate it back into the engine. Before the intake air enters the intake manifold, the compressor increases its mass, compresses it, and increases its pressure.

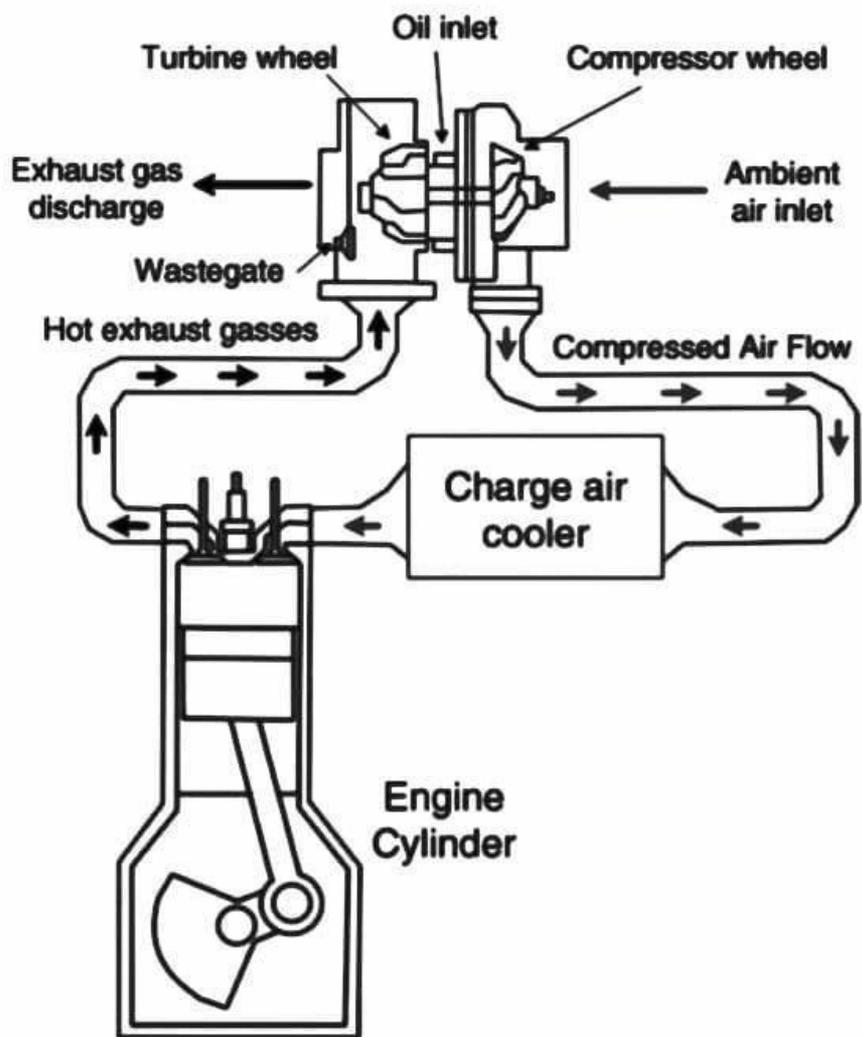


Figure 1.8 A schematic of a turbocharging system

Turbochargers are capable of providing volumetric efficiency greater than 100% because in these engine types, the intake manifold pressure exceeds atmospheric pressure. However, the engine efficiency comes at the expense of reduced power from the cylinders. This reduction occurs because the turbine in the exhaust causes the exhaust stroke of the engine to push harder against higher backpressure. The two major problems of turbochargers are turbo lag and high intake air temperature. Turbo lag is a sluggish (delayed) response from the engine during the initial push on the throttle pedal. It occurs due to the initial inertia of the turbocharger. Essentially, at low engine speeds, the exhaust gas flow is not strong enough to push the turbine quickly. The compression of the intake air results in increased air pressure, which in turn causes the temperature to rise. Excessive intake air temperature and pressure may cause detonation (engine knocking) or pre-ignition phenomena, which reduces the output power. Pre-ignition is an abnormal combustion in which high pressure and temperature cause the air-fuel mixture to ignite earlier than it would by spark plug fire. To cool down the intake air, an intercooler located in the middle of the piping between the turbocharger's compressor and the engine's air intake valve is integrated. The waste-gate usually regulates and limits air intake pressure. The waste-gate controls air pressure by bypassing some of the exhaust gas flow before entering the turbine as it reaches the intake pressure threshold.

An advanced type of turbocharger technology is the variable turbine geometry turbocharger, also known as a variable geometry turbocharger or a variable nozzle turbine. This type of turbocharger contains a set of adjustable vanes in the turbine housing. These vanes are modified in angle throughout the engine speed to maximize and control boost pressure over a wide range of engine operations. The vanes guide the exhaust flow towards the turbine while an actuator

adjusts their angles. The purpose of a variable geometry turbocharger is to partially close the vanes at low-speed conditions. Partially closing these vanes directs exhaust gas towards the turbine and pushes the turbine blades to the right angle. This will cause the turbine to spin faster before the engine reaches proper speed. At higher speeds where the exhaust flow is sufficiently strong, the vanes open completely to capture the high kinetic energy of the exhaust gas. This reduces the exhaust pressure in the turbocharger by removing the waste-gate from the circuit.

A variable geometry turbocharger reduces turbo lag at low engine speeds, provides cleaner exhaust gas, and improves fuel economy while maintaining power and performance. Furthermore, these turbochargers also effectively reduce particulate matter emissions from diesel engines by providing lean combustion in the engine. Diesel engine vehicles mainly use variable geometry turbochargers; they have achieved some success with gasoline engine vehicles as well. The high temperature of exhaust gases is the main obstruction preventing complete integration of variable geometry turbochargers within gasoline engines.

1.3.2 Catalytic Converters

Positioned in the exhaust pipe, catalytic converters are emission control devices that convert unsafe exhaust emissions into harmless compounds through a combination of catalysts. A catalyst is a chemical material that increases the rate of a chemical reaction without changing itself in the process. Platinum, rhodium, and palladium are the most commonly used catalysts.

The catalytic converter plays a significant role in vehicle emission reduction, which is why it is the main emission control technology used in vehicles. However, leaded fuels adversely affect the efficiency of catalytic converters. These fuels form deposits that coat the catalyst and prevent proper contact between exhaust gasses and catalysts. The catalytic converters used in gasoline vehicles include oxidation (two-way) catalysts and oxidation–reduction (three-way) catalysts, while diesel vehicles use diesel oxidation catalysts, selective catalytic reduction, and nitrogen–oxide adsorber catalysts. Important factors that affect the performance of a catalytic converter are catalyst temperatures, mixture air–fuel ratio, and hydrocarbon mix.

1.3.2.1 The Two-Way Catalyst

Two-way catalysts use an oxidation process to convert carbon monoxide and hydrocarbons to carbon dioxide and water. Vehicles used the oxidation catalyst from the mid-1970s until the 1980s, but the invention of the three-way catalyst has rendered it obsolete in modern vehicles.

1.3.2.2 The Three-Way Catalyst

Almost all modern vehicles have three-way catalysts. They convert nitrogen oxide back into nitrogen and oxygen, and convert carbon monoxide and hydrocarbons into water and carbon dioxide. When the air–fuel ratio is close to stoichiometric, it is possible to achieve the maximum conversion efficiency for all three pollutants. In these circumstances, three-way catalysts are capable of oxidizing hydrocarbons and carbon monoxide while reducing nitrogen–oxide emissions. A fuel-ratio range between 0.98 and 1.003 can achieve a high conversion efficiency. However, this range is quite narrow and limiting. For leaner mixtures, the efficiency of the catalyst in conversion of hydrocarbons and monoxide increases, however, the catalyst is inefficient at reducing nitrogen–oxide emission. In contrast, for richer mixtures, the conversion efficiency of nitrogen–oxide emissions increases while the efficiency of carbon monoxide and hydrocarbons decreases.

An ECU helps keep a three-way catalyst at its optimal operation conditions, which greatly depends on the catalytic temperature. In other words, high conversion efficiency can be achieved if the catalytic temperature reaches a certain value known as “light off temperature,” which is usually in the range of 200 °C–300 °C. By contrast, the efficiency of catalysts can decrease because of overheated conditions, which can occur due to improper engine tuning, inadequate rich air–fuel mixtures, or cylinder misfiring.

1.3.2.3 Diesel Oxidation Catalyst (DOC)

The lean combustion of diesel engines prevents the use of three-way catalysts. As such, most diesel engines use a diesel oxidation catalyst (DOC), which converts carbon monoxides and hydrocarbons to carbon dioxide and water through an oxidation process, while also reducing soot mass. However, DOCs are inefficient in reducing nitrogen oxides and particulate matter. Additionally, they are capable of oxidizing sulfur dioxide that exists in diesel exhaust (specifically in heavy-duty vehicles). The oxidation of sulfur dioxide forms sulfate particles, which in turn increase the amount of total particle emissions. As such, DOCs need to be designed in a way that balances a sufficient reduction of hydrocarbons and carbon monoxides with reasonable amounts of sulfur-dioxide. The efficiency of catalysts can be improved if they are used in conjunction with other emission control technologies. The effect of DOCs on fuel consumption is not substantial. Light-duty diesel vehicles frequently use DOCs, although they have been shown to be effective in heavy-duty vehicles as well.

1.3.2.4 Selective Catalytic Reduction (SCR)

Selective catalytic reduction (SCR) is one of the most efficient emission control technologies. SCR helps to reduce nitrogen oxide emissions to near zero levels through a catalytic reaction while also providing good fuel economy and durability. It is possible to apply SCR to all types of diesel-powered vehicles (light, medium, heavy-duty) without compromising engine power and performance. SCR functions by injecting diesel exhaust fluid (DEF), a liquid containing urea and water, into the exhaust stream, which is just ahead of the SCR converter. Urea is a nitrogen compound that hydrolyses into ammonia (NH_3) when heated. In the presence of a catalyst, the ammonia reacts with the exhaust stream to produce nitrogen and water vapor. However, some un-reacted ammonia may be released into the atmosphere as well. This is known as an “ammonia slip” and can be caused by over-injected DEF in the gas stream, low temperature conditions, or a degraded catalyst.

A highly controlled system regulates the amount of injected DEF, it adequately distributes the ammonia in the gas stream and provides a consistent gas velocity for the catalyst. The control system works either as an open-loop or closed-loop system. The open-loop system uses a nitrogen oxide estimation algorithm to estimate the amount of nitrogen oxide available in the exhaust stream. The algorithm uses operation conditions such as engine speed, exhaust temperature, and load to determine the amount of DEF to inject. The closed-loop system obtains data through a sensor that measures nitrogen oxide concentration; from this it calculates the amount of DEF to inject. A concern during the conversion process of this catalyst is the possible formation of sulfate. As such, it is important to use low sulfur fuel to avoid further particulate emissions and to enhance the catalyst efficiency. A disadvantage of the SCR system is its dependency on a tank to store DEF liquid, if the tank runs dry, the SCR system stops functioning.

1.3.2.5 Nitrogen–Oxide (NO_x) Adsorber Catalyst

As opposed to gasoline engines, diesel engines usually run at lean fuel mixture conditions. However, recently, the design of lean-burn gasoline engines suits passenger vehicles as well. A lean-burn gasoline engine provides a higher compression ratio, better performance, superior fuel efficiency, and lower carbon monoxide emissions than that of conventional gasoline engines. These benefits, however, come at the expense of higher production of nitrogen–oxide emissions. These emissions occur as a result of the increased levels of oxygen in the fuel mixture and exhaust gases. Since a conventional three-way catalyst does not effectively reduce nitrogen oxides under lean conditions, the mass production of such vehicles has been a subject of great debate.

A NO_x adsorber (known as a lean NO_x trap or LNT) is a catalyst designed to reduce nitrogen–oxide emissions; it is most effective in lean-burn engines. An LNT system stores nitrogen–oxide emissions in a catalyst under lean conditions. It then catalytically reduces the trapped nitrogen oxide to nitrogen when the engine is running under rich conditions. The cycle in which a catalytic reaction between excess unburned hydrocarbons and nitrogen oxide converts the trapped nitrogen oxide to nitrogen is called the nitrogen–oxide regeneration cycle. The operating temperature, system responsiveness, and diesel sulfur content are the main factors affecting the catalyst efficiency. Like other catalysts, LNT offers superior performance at higher operating temperatures and lower sulfur fuels. The main advantages of LNT technology include high efficiency in nitrogen oxide emission reduction, low light-off temperature, and a cost-effective system. However, LNT adversely affects vehicle fuel economy because of the fuel requirements and burn conditions of the nitrogen oxide regeneration cycle. While the effectiveness of LNT under stoichiometric conditions is less than that of three-way catalysts, it still provides significant benefits under lean conditions.

1.3.3 The Diesel Particulate Filter (DPF)

A diesel particulate filter (DPF) collects and removes diesel particulate matters or soot from the exhaust of the engine by passing exhaust gases through the walls between numerous channels (see Figure 1.9). A DPF accumulates soot and particulate matters over time; however, since

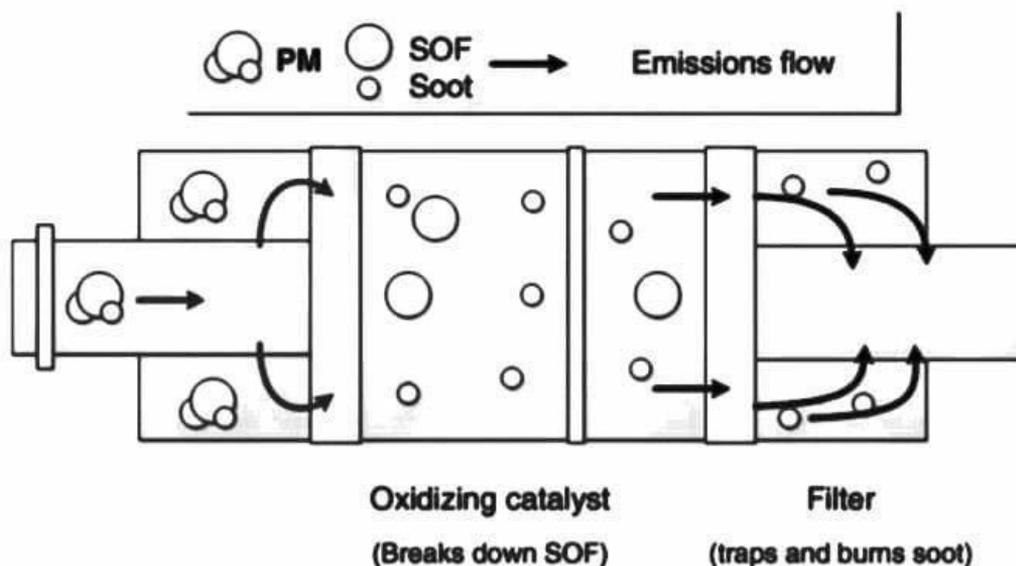


Figure 1.9 A schematic of a passive diesel particulate filter

filters have limited capacity, they need to be removed or cleaned in order to avoid backpressure blockage on the engine. If left dirty, this blockage may result in engine damage or destruction.

Some filters are designed for single use and can easily be discarded or replaced. For other filters, it is necessary to remove the accumulated particulate matters. A practical approach to dispose of the trapped materials is to burn or oxidize the particulate matters within the filter once the exhaust gases reach a certain temperature. The process of cleaning by burning the trapped materials is called filter regeneration.

A passively regenerated filter is a filter regenerated by available exhaust heat or by using a catalyst. On the other hand, an actively regenerated filter is one that uses active means during the filter regeneration process. For example, actively regenerated filters can either use the injection of diesel fuel into an upstream of DOC, or utilize a fuel burner that heats the filter to particulate matters combustion temperatures. Passive regeneration cannot be used if the exhaust temperature is lower than the threshold, whereas in active regeneration techniques, it is possible to integrate various engine controls to provide filter regeneration conditions on demand. Integrating a combination of passive and active strategies can ensure the completion of filter regeneration under all possible vehicle operating conditions. Additionally, reduction in particulate matters and nitrogen oxide emissions can be simultaneously achieved if a diesel particulate filter is used in conjunction with exhaust gas recirculation, nitrogen-oxide adsorber catalysts, or selective catalytic reduction.

1.3.4 Exhaust Gas Recirculation (EGR)

Figure 1.10 depicts a schematic of an exhaust gas recirculation (EGR) for a gasoline engine. This technology reduces nitrogen oxide emissions in both gasoline and diesel engines during operating periods in which high combustion temperatures occur. The principal function of an EGR is to recirculate a controlled portion of exhaust gases into the engine combustion chamber

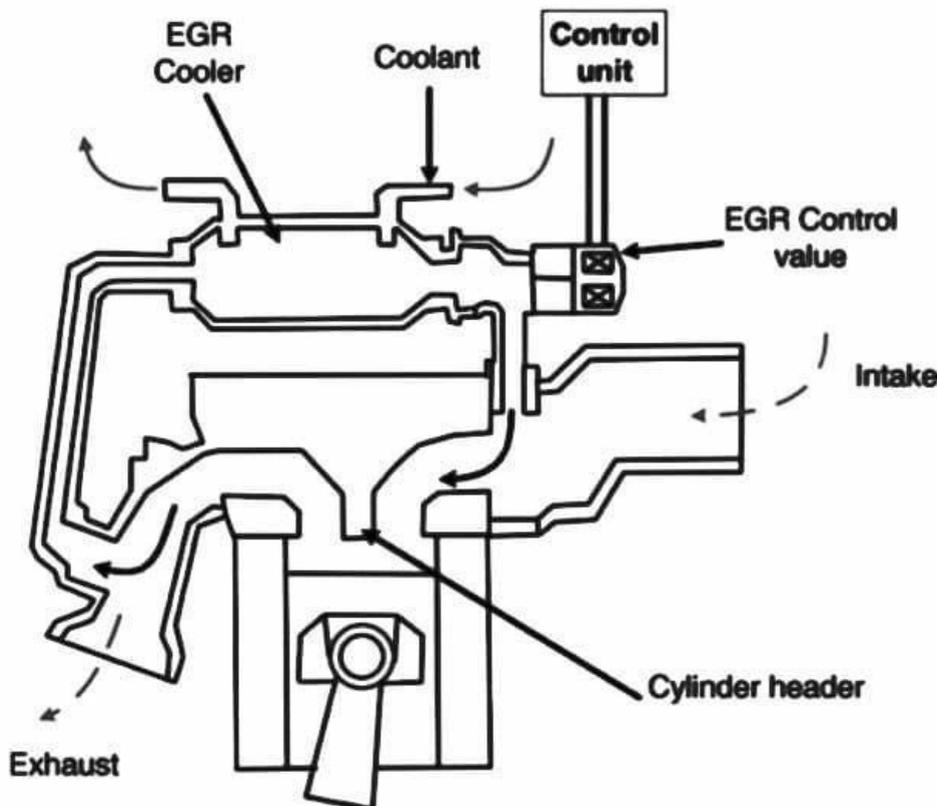


Figure 1.10 Schematic of the EGR loop for a gasoline engine

through a valve. This technology recirculates some exhaust gases to the intake manifold where the temperature of recirculated exhaust gases usually decreases by passing gases through an intercooler. The recirculated exhaust gases subsequently mix with the incoming intake manifold air, resulting in a diluted air–fuel mixture. This dilution causes a lower heat release and a lower peak cylinder temperature, which subsequently reduces nitrogen oxide formation. The recirculated exhaust gases must mix homogeneously with incoming air to have a consistent EGR distribution per cylinder. Improper EGR distribution may cause one cylinder to receive higher amounts of EGR, resulting in a higher rate of particulate matters emissions. Conversely, cylinders receiving low amounts of EGR produce higher rates of nitrogen oxide emissions. The EGR system prolongs the engine life because it reduces the peak of combustion temperature.

In a gasoline engine, an EGR system provides different types of exhaust gas flow. For example, EGR systems use a high flow of exhaust gases during operating conditions with high combustion temperatures, such as cruising and mid-range acceleration. Likewise, it provides a low flow of gases during low speed or light load conditions. The EGR system stops recirculating gases at full power demands as the recirculation process reduces engine operating efficiency, and also during idling to avoid higher level of emissions.

It is important to precisely regulate the amount of recirculated exhaust gases. This amount is a trade-off between a reduction in nitrogen oxide emissions and engine efficiency. Excessive recirculation of exhaust gases degrades the engine performance and efficiency, while minimal recirculation results in engine knocking and a decrease in EGR efficiency. Modern vehicles utilize ECU, sensors, and servo-driven EGR valves to balance engine efficiency and vehicle drivability by regulating the recirculation flow rate.

In diesel engines, reducing nitrogen–oxide emission occurs at the cost of an increase in particulate matters' emissions. The two main types of EGR systems used by diesel engines include high pressure loop EGR and low-pressure loop EGR (Figure 1.11). A high-pressure loop EGR diverts the exhaust gases before they reach the turbocharger turbine section. Conversely, the low-pressure loop EGR captures the exhaust gases after passing through

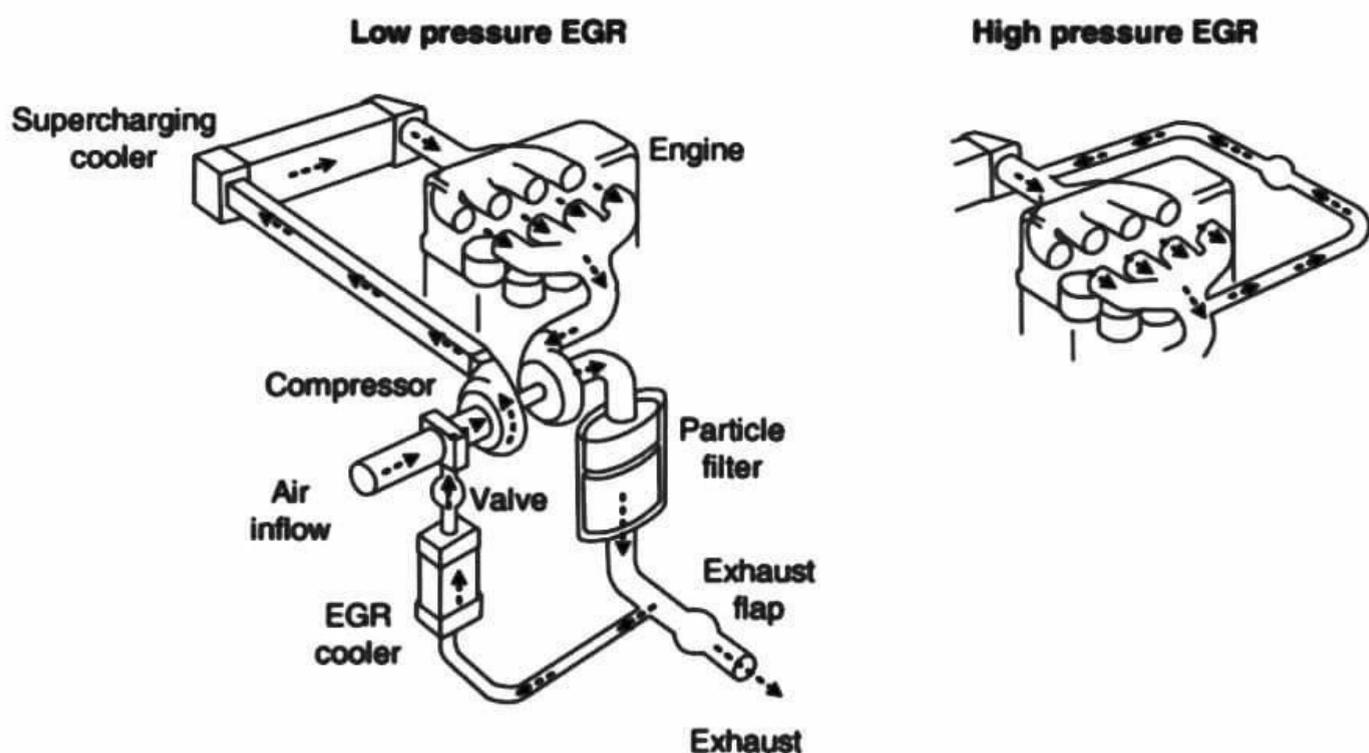


Figure 1.11 The EGR loop for a diesel engine

the turbocharger and the diesel particulate filter. Incorporating a diesel particulate filter or an oxidation catalyst in an EGR loop helps reduce the amount of particulate matters re-routed to the combustion process.

Integrating a combination of high- and low-pressure loop systems with a variable geometry turbocharger can enhance the EGR system efficiency over a wide range of operating conditions. The low-pressure EGR recirculates exhaust gases at low engine speeds and loads, while high-pressure EGR functions under higher engine speeds and loads. An optimized combination of the technologies will provide a more effective and efficient reduction of nitrogen oxide.

1.3.5 Crankcase Emission Control System

Blow-by gases are gases that leak into the crankcase during power or compression strokes while an engine is running. They are composed of mostly unburnt or partially burnt hydrocarbons and combustion by-products, which leak through the clearances between the piston rings and the cylinder walls.

The ventilation of blow-by gases helps prevent pressure build-up and increases engine longevity. In uncontrolled crankcase emission, a road draft tube releases blow-by gases and other vapors directly into the atmosphere. Hydrocarbon and particulate matters emissions are the classifications of these gases, and, if they enter the cabin, can be a significant source of emission exposure for drivers and passengers.

The crankcase emission control system, shown in Figure 1.12, is designed to re-burn the blow-by gases by diverting them into the intake system of a gasoline or diesel engine. When a gasoline engine vehicle is moving, fresh air flows to the crankcase through an air inlet path called the breather. The incoming air transfers and recirculates the blow-by gases from the crankcase into the intake system, allowing it to mix with an incoming stream of air.

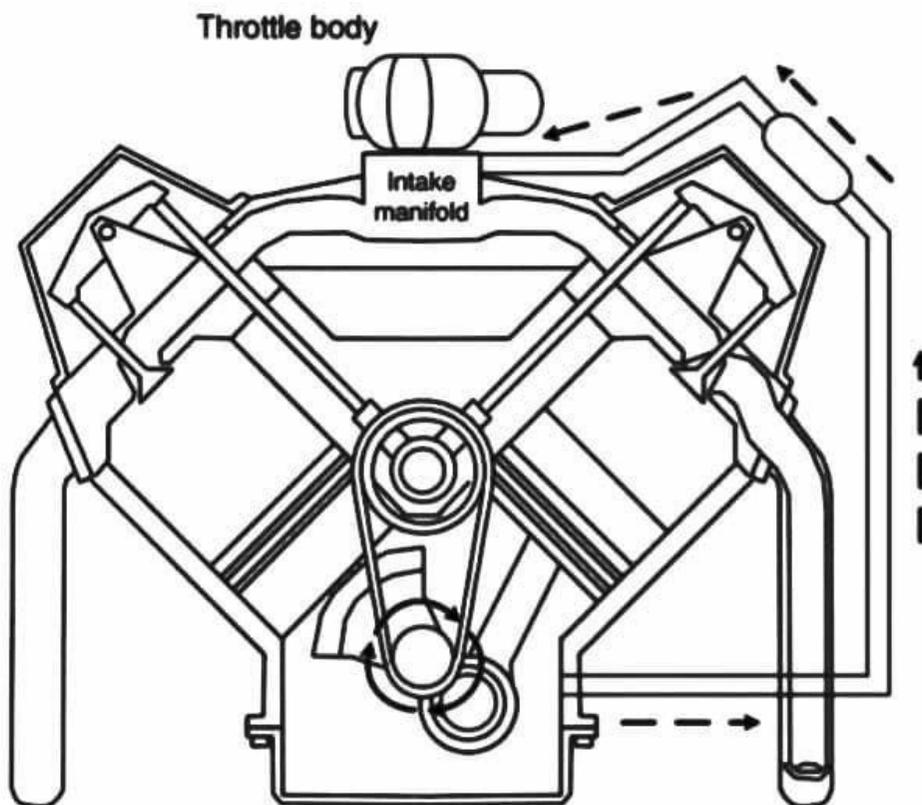


Figure 1.12 Crankcase emission control system of a gasoline engine

A check valve adjusts the gas flow between the crankcase and the intake manifold; the positive crankcase ventilation (PCV) valve controls the intake system pressure of the check valve. Then the diverted mix of air and blow-gases is injected into the combustion chamber where it is re-burned. Valve malfunctions may result in the blockage of blow-by gases and since the gases are under pressure, they may find other ways to escape from the crankcase to other parts of the engine compartment. These malfunctions can cause damage to engine parts, and result in oil leaks and sludge formation within the engine.

In a diesel engine, a multi-stage filter collects and returns the emitted lube oil to the engine's sump. Then, filtered gases reroute with a balanced differential pressure to the intake system. The crankcase emission control system of diesel vehicles often includes filter housing, a pressure regulator, a pressure relief valve, and an oil check valve.