UNIT-IV
FUEL CELLS

Fuel Cell

Introduction

Fuel cells are hardly a new idea. They were invented in about 1840, but they are yet to really make their mark as a power source for electric vehicles. However, this might be set to change over the next 20 or 30 years. Certainly most of the major motor companies are spending very large sums of money developing fuel cell powered vehicles. The basic principle of the fuel cell is that it uses hydrogen fuel to produce electricity in a battery- like device to be explained in the next section. The basic chemical reaction is:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1}$$

The product is thus water, and energy. Because the types of fuel cell likely to be used in vehicles work at quite modest temperatures (~85°C) there is no nitrous oxide produced by reactions between the components of the air used in the cell. A fuel cell vehicle could thus be described as zero-emission. Furthermore, because they run off a fairly normal chemical fuel (hydrogen), very reasonable energies can be stored, and the range of fuel cell vehicles is potentially quite satisfactory. They thus offer the only real prospect of a silent zero-emission vehicle with a range and performance broadly comparable with IC engine vehicles. It is not surprising then that there have, for many years, been those who have seen fuel cells as a technology that shows great promise, and could even make serious inroads into the domination of the internal combustion engine.

Main issues in the fuel cell

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

- *Cost:* Fuel cells are currently far more expensive than IC engines, and even hybrid IC/electric systems.
- *Water management:* Water management is important and difficult issue with automotive fuel cells.
- *Cooling:* The thermal management of fuel cells is actually rather more difficult than for IC engines.
- *Hydrogen supply:* Hydrogen is the preferred fuel for fuel cells, but hydrogen is very difficult to store and transport.

However, there is great hope that these problems can be overcome, and fuel cells can be the basis of less environmentally damaging transport.

Hydrogen Fuel Cells: Basic Principles

Electrode reactions

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

To understand this we need to consider the separate reactions taking place at each electrode. These important details vary for different types of fuel cell, but if we start with a cell based on an acid electrolyte, we shall consider the simplest and the most common type.

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

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{2}$$

This reaction releases energy. At the cathode, oxygen reacts with electrons taken from the electrode, and H+ ions from the electrolyte, to form water.

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

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

Different electrolytes

The reactions given above may seem simple enough, but they do not proceed rapidly in normal circumstances. Also, the fact that hydrogen has to be used as a fuel is a disadvantage. To solve these and other problems many different fuel cell types have been tried. The different types are usually distinguished by the electrolyte that is used, though there are always other important differences as well.

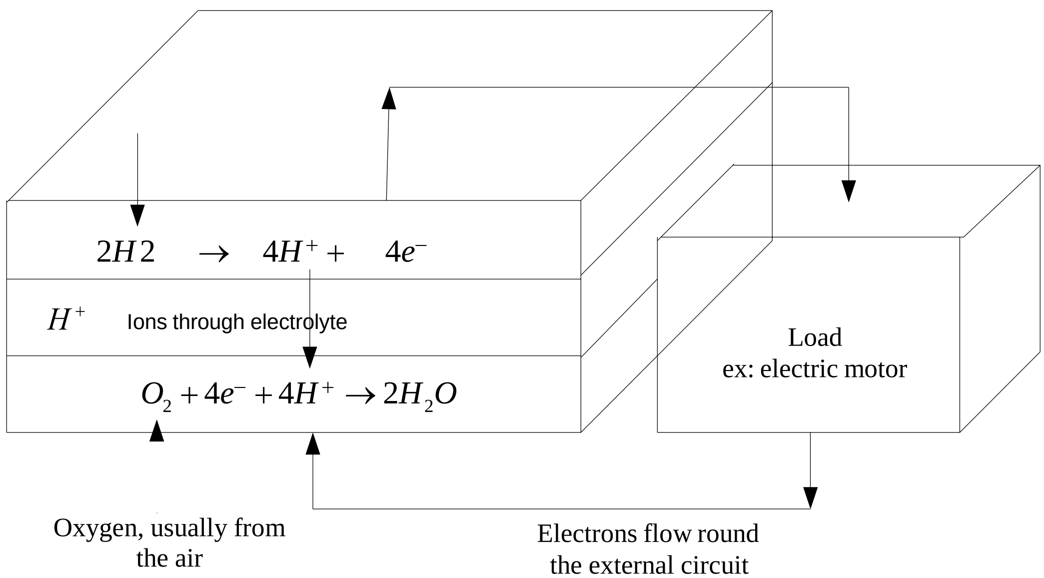


Fig. 1 The reactions at the electrodes, and the electron movement, in a fuel cell with an acid Electrolyte

Table I: Data for different types of fuel cell

Fuel cell type	Mobile ion	Operating temp.	Applications and notes
Alkaline (AFC)	OH^{-}	50–200°C	Used in space vehicles, e.g. Apollo, Shuttle.
Proton exchange membrane (PEMFC)	H^{+}	30-100°C	Vehicles and mobile applications, and for lower power CHP systems
Direct methanol(DMFC)	H^{+}	20-90°C	Suitable for portable electronic systems of low power, running for long times
Phosphoric acid (PAFC)	H^{+}	220°C	Large numbers of 200kW CHP systems in use
Molten carbonate (MCFC)	CO_3^{2-}	650°C	Suitable for medium to large scale CHP systems, up to MW capacity
Solid oxide (SOFC)	O^{2-}	500-1000°C	Suitable for all sizes of CHP systems, 2 kW to multi MW

The situation now is that six classes of fuel cell have emerged as viable systems for the present and near future. Basic information about these systems is given in Table I. As well as facing up to different problems, the various fuel types also try to play to the strengths of fuel cells in different ways. The PEM fuel cell capitalizes on the essential simplicity of the fuel cell. The electrolyte is a solid polymer, in which protons are mobile. The chemistry is the same as the acid electrolyte fuel cell of Fig. 1. With a solid and immobile electrolyte, this type of cell is inherently simple; it is the type that shows by far the most promise for vehicles, and is the type used on all the most impressive demonstration fuel cell vehicles. This type of fuel cell is the main focus of this chapter. PEM fuel cells run at quite low temperatures, so the problem of slow reaction rates has to be addressed by using sophisticated catalysts and electrodes. Platinum is the catalyst, but developments in recent years mean that only minute amounts are used, and the cost of the platinum is a small part of the total price of a PEM fuel cell.

One theoretically very attractive solution to the hydrogen supply problem is to use methanol1 as a fuel instead. This can be done in the PEM fuel cell, and such cells are called direct methanol fuel cells. ‘Direct’ because they use the methanol as the fuel as it is, in liquid form, as opposed to extracting the hydrogen from the methanol using one of the methods. Unfortunately these cells have very low power, and for the foreseeable future at least their use will be restricted to applications requiring slow and steady generation of electricity over long periods. A demonstration DMFC powered go-kart has been built, but really the only likely application of this type of cell in the near future is in the rapidly growing area of portable electronics equipment.

Although PEM fuel cells were used on the first manned spacecraft, the alkaline fuel cell was used on the Apollo and is used on the Shuttle Orbiter. The problem of slow reaction rate is overcome by using highly porous electrodes, with a platinum catalyst, andsometimes by operating at quite high pressures. Although some historically important alkaline fuel cells have operated at about 200◦C, they more usually operate below 100◦C. The alkaline fuel cell has been used by a few demonstration electric vehicles, always in hybrid systems with a battery. They can be made more cheaply than PEMFCs, but they are lower in power, and the electrolyte reacts with carbon dioxide in the air, which make terrestrial applications difficult.

Fuel cell electrodes(Construction of Fuel cell)

Fig. 2 is another representation of a fuel cell. Hydrogen is fed to one electrode, and oxygen, usually as air, to the other. A load is connected between the two electrodes, and current flows. However, in practice a fuel cell is far more complex than this. Normally the rate of reaction of both hydrogen and oxygen is very slow, which results in a low current, and so a low power. The three main ways of dealing with the slow reaction rates are: the use of suitable catalysts on the electrode, raising the temperature, and increasing the electrode area.

The first two can be applied to any chemical reaction. However, the third is special to fuel cells and is very important. If we take a reaction such as that of Eq. 3, we see that oxygen gas, and H^+ ions from the electrolyte, and electrons from the circuit are needed, all three together. This ‘coming together’ must take place on the surface of the electrode. Clearly, the larger the electrode area, the more scope there is for this to happen and the greater the current. This is very important. Indeed, electrode area is such a vital issue that the performance of a fuel cell design is often quoted in terms of the current *per* cm^2.

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

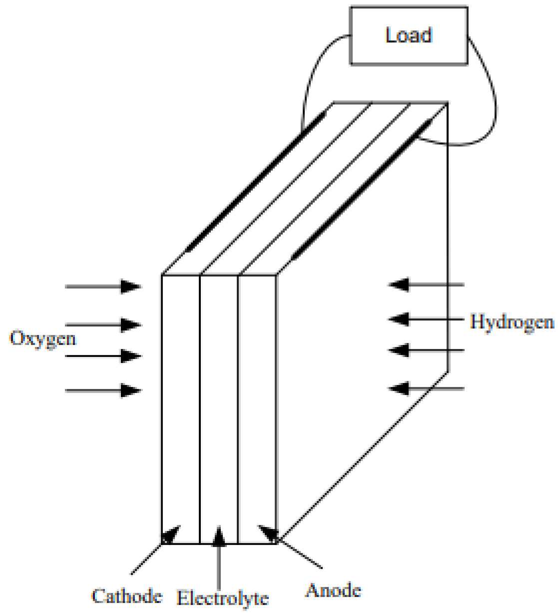


Fig. 2 Basic cathode-electrolyte-anode construction of a fuel cell.

The reactants need to be brought into contact with the catalyst, and a good electrical contact needs to be made with the electrode surface. Also, in the case of the cathode, the product water needs to be removed. These tasks are performed by the 'gas diffusion layer', a porous and highly conductive material such as carbon felt or carbon paper, which is layered on the electrode surface.

Fuel Cell Thermodynamics – Introduction

Fuel cell efficiency and efficiency limits

One of the attractions of fuel cells is that they are not heat engines. Their thermodynamics are different, and in particular their efficiency is potentially greater as they are not limited by the well-known Carnot limit that impinges on IC and other types of fuel burning engines. However, as we shall see, they do have their own limitations,and while fuel cells are often more efficient than IC engines, the difference is sometimes exaggerated.

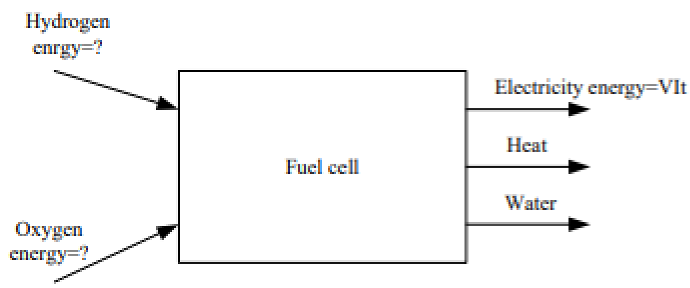


Fig. 3 Fuel cell inputs and outputs

At first we must acknowledge that the efficiency of a fuel cell is not straightforward to define. In some electrical power generating devices it is very clear what form of energy is being converted into electricity. With a fuel cell such energy considerations are much more difficult to visualize. The basic operation has already been explained, and the input and outputs are shown in Fig. 3. The electrical power and energy output are easily calculated from the well known formulas:

$$\text{Power} = VI \text{ and Energy} = VIt \tag{4}$$

However, the energy of the chemical inputs and output is not so easily defined. At a simple level we could say that it is the chemical energy of the H_2, O_2 and H_2O that is in question. The problem is that chemical energy is not simply defined, and terms such as enthalpy, Helmholtz function and Gibbs free energy are used. In recent years the useful term 'energy' has become quite widely used, and the concept is particularly useful in high temperature fuel cells, though we are not concerned with these here. There are also older (but still useful) terms such as calorific value.

In the case of fuel cells it is the Gibbs free energy that is important. This can be defined as the energy available to do external work, neglecting any work done bychanges in pressure and/or volume. In a fuel cell the external work involves moving electrons round an external circuit; any work done by a change in volume between the input and output is not harnessed by the fuel cell. Energy is *all* the external work that can be extracted, including that due to volume and pressure changes. Enthalpy, simply put, is the Gibbs free energy plus the energy connected with the entropy. The enthalpy *H*, Gibbs free energy *G* and entropy *S* are connected by the well-known equation:

$$G = H - TS \tag{5}$$

The energy that is released by a fuel cell is the change in Gibbs energy before and after a reaction, so the energy released can be represented by the equation:

$$\Delta G = G_{outputs} - G_{inputs} \tag{6}$$

However, the Gibbs free energy change is *not constant*, but changes with temperature and state (liquid or gas). Table II below shows ΔG for the basic hydrogen fuel cell reaction for a number of different conditions. Note that the values are negative, which means that energy is released.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$$

Table 2: ΔG for the reaction H_2 + 1_2 O2 → H_2O at various temperatures

Form of water product	Temperature (˚C)	ΔG (kJ/mole)
Liquid	25	- 237.2
Liquid	80	-228.2
Gas	80	-226.1
Gas	100	-225.2
Gas	200	-220.4
Gas	400	-210.3
Gas	600	-199.6
Gas	800	-188.6
Gas	1000	-177.4

If there are no losses in the fuel cell, or as we should more properly say, if the process is reversible, then all this Gibbs free energy is converted into electrical energy. We could thus define the efficiency of a fuel cell as:

$$\frac{\text{electrical energy produced}}{\text{Gibbs free energy change}} \tag{8}$$

Since a fuel cell uses materials that are usually burnt to release their energy, it would make sense to compare the electrical energy produced with the heat that would be produced by burning the fuel. This is sometimes called the calorific value, though a more precise description is the change in enthalpy of formation. Its symbol is ΔH. As with the Gibbs free energy, the convention is that ΔH is negative when energy is released. So to get a good comparison with other fuel using technologies, the efficiency of the fuel cell is usually defined as:

$$\frac{\text{electrical energy produced per mole of fuel}}{-\Delta H} \tag{9}$$

However, even this is not without its ambiguities, as there are two different values that we can use for ΔH. For the burning of hydrogen:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \text{ (steam)}$$

$$\Delta H = \text{-241.83 } kJ / mole$$

whereas if the product water is condensed back to liquid, the reaction is:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \text{ (liquid)}$$

$$\Delta H = \text{-285.84 } kJ / mole$$

The difference between these two values for ΔH (44.01 kJ/mole) is the molar enthalpy of vaporization of water. The higher figure is called the higher heating value (HHV), and the lower, quite logically, the lower heating value (LHV). Any statement of efficiency should say whether it relates to the higher or lower heating value. If this information is not given, the LHV has probably been used, since this will give a higher efficiency figure.

We can now see that there is a limit to the efficiency, if we define it as in Eq. 4. The maximum electrical energy available is equal to the change in Gibbs free energy, so:

$$Maximum\ efficiency\ possible = \frac{\Delta G}{\Delta H} \times 100\% \tag{12}$$

This maximum efficiency limit is sometimes known as the thermodynamic efficiency. Table III gives the values of the efficiency limit, relative to the higher heating value, for a hydrogen fuel cell. The maximum voltage obtainable from a single cell is also given.

The graphs in Fig. 5 show how these values vary with temperature, and how they compare with the Carnot limit, which is given by the equation:

$$Carnot\ limit = \frac{T_1 - T_2}{T_1} \tag{13}$$

where T_1 is the higher temperature, and T_2 the lower, of the heat engine. The graph makes clear that the efficiency limit of the fuel cell is certainly not 100%, as some supporters of fuel cells occasionally claim. Indeed, above the 750°C the efficiency limit of the hydrogen fuel cell is actually less than for a heat engine. Nevertheless, the PEM fuel cells used in vehicles operate at about 80°C, and so their theoretical maximum efficiency is actually much better than for an IC engine.

Efficiency and the fuel cell voltage

A very useful feature of fuel cells is that their efficiency can be very easily found from their operating voltage. The reasoning behind this is as follows. If *one* mole of fuel is reacted in the cell, then *two* moles of electrons are pushed round the external circuit;

Table 3: ΔG, maximum EMF, and efficiency limit (HHV) for hydrogen fuel cells

Form of water product	Temp °C	ΔG kJ/mole−1	Max. EMF	Efficiency limit
Liquid	25	-237.2	1.23V	83%
Liquid	80	-228.2	1.18 V	80%
Gas	100	-225.3	1.17 V	79%
Gas	200	-220.4	1.14 V	77%
Gas	400	-210.3	1.09 V	74%
Gas	600	199.6	1.04 V	70%
Gas	800	-188.6	0.98 V	66%
Gas	1000	-177.4	0.92 V	62%

$$Energy = Charge \times Voltage \quad (14)$$

The Faraday constant F gives the charge on one mole of electrons. So, when one mole of hydrogen fuel is used in a fuel cell, if it were 100% efficient, as defined by Eq. 4, then we would be able to say that:

$$Energy = 2F \times V_{100\%} = \Delta H$$
$$and \text{ thus } V_{100\%} = \frac{\Delta H}{2F} \quad (15)$$

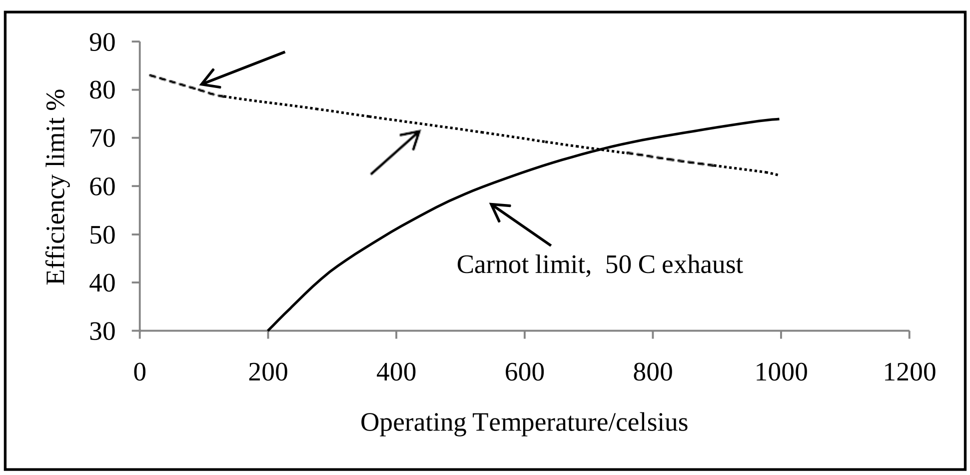


Fig. 5: Maximum hydrogen fuel cell efficiency at standard pressure, with reference to the higher heating value.

The two values for ΔH given above, we can easily calculate that the '100% efficient' voltage for a single cell is 1.48V if using the HHV or 1.25V if using the LHV. Now of course a fuel cell never is, and we have shown in the last section never can be, 100% efficient. The actual fuel cell voltage will be a lower value, which we can call V_c. Since voltage and electrical energy are directly proportional, it is clear that

$$Fuelcellefficiency = \frac{Vc}{V_{100\%}} = \frac{Vc}{1.48}$$

Clearly it is very easy to measure the voltage of a fuel cell. In the case of a stack of many cells, remember that the voltage of concern is the average voltage one cell, so the system voltage should be divided by the number of cells. The efficiency can thus be found remarkably easily.

It is worth noting in passing that the maximum voltage of a fuel cell occurs when 100% of the Gibbs free energy is converted into electrical energy. Thus we have a 'sister' equation to Eq. 4, giving the maximum possible fuel cell voltage:

$$V_{\max} = \frac{\Delta G}{2F}$$

This is also a very important fuel cell equation, and it was used to find the figures shown in the fourth column of Table III.

Fuel cell voltage, current and power:

The power output of a fuel cell stack is a product of stack voltage and current:

$$W_{FC} = V_{st} \cdot I$$

The current is a product of the current density and the cell active area:

$$I = i * A_{cell}$$

The cell potential and the current density are related by the polarization curve:

$$V_{cell} = f(i)$$

The total stack potential is the sum of the stack voltages or the product of the average cell potential and number of cells in the stack:

$$V_{st} = \sum_{i=1}^{N_{cell}} V_i = \overline{V}_{cell} * N_{cell}$$

The fuel cell stack efficiency can be approximated with the following equation:

$$\eta_{stack} = \frac{V_{cell}}{1.482}$$

Practical fuel cell voltages

In practice the actual cell voltage is less than this. Now of course this applies to ordinary batteries too, as when current is drawn out of any electric cell the voltage falls, due to internal resistances. However, with a fuel cell this effect is more marked than with almost all types of conventional cell. **Figure 6** shows a typical voltage/current density curve for a good PEM fuel cell. It can be seen that the voltage is always less, and is often much less, than the 1.18V that would be obtained if all of the Gibbs energy were converted into electrical energy.

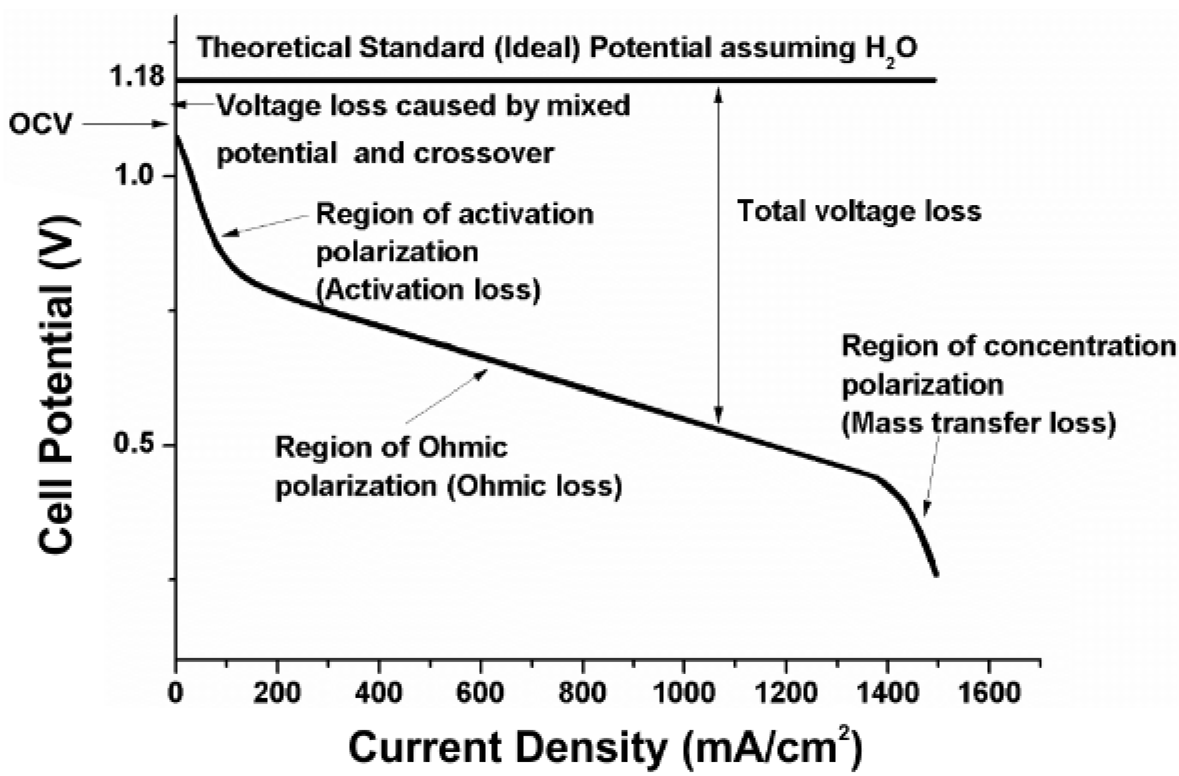


Fig. 6 Graph showing the voltage from a typical good quality PEM fuel cell operating on air at about 80◦C

There are three main reasons for this loss of voltage, as detailed below.

- **Activation loss:** The energy required to drive the reactions at the electrodes, usually called the activation energy, causes a voltage drop. This is especially a problem at the air cathode, and shows itself as a fairly constant voltage drop. This explains the initial fall in voltage even at quite low currents.
- **Ohmic loss:** The resistance of the electrolyte and the electrodes causes a voltage drop that more or less follows Ohm’s law, and causes the steady fall in voltage over the range of currents. This is usually called the Ohmic voltage loss.
- **Mass transfer loss**: At very high currents, the air gets depleted of oxygen, and the remnant nitrogen getsin the way of supplying fresh oxygen. This result is a fall in voltage, as theelectrodes are short of reactant. This problem causes the more rapid fall in voltageat higher currents, and is called mass transfer or concentration voltage loss.

SIZING OF FUEL CELL:

The parametric design of the fuel cell-powered hybrid drive train includes the design of the traction motor power, the fuel cell system power, and the PPS power and energy capacity.

a)Motor Power Design:

The motor power is required to meet the acceleration performance of the vehicle. The power rating of the motor drive can be estimated, according to the acceleration performance (time used to accelerate the vehicle from zero speed to a given speed), using the following equation:

$$P_t = \frac{\delta M_v}{2t_a}(V_f^2 + V_b^2) + \frac{2}{3}M_v g f_r V_f + \frac{1}{5}\rho_a C_D A_f V_f^3,$$

where Mv is the total vehicle mass in kg, ta is the expected acceleration time in sec, Vb is the vehicle speed in m/s, corresponding to the motor-based speed (see Figure 7.6), Vf is the final speed of the vehicle accelerating in m/s, g is gravity acceleration in 9.80 m/s2 , fr is the tire rolling resistance coefficient, ρa is the air density in 1.202 kg/m3 , Af is the front area of the vehicle in m2 , and CD is the aerodynamic drag coefficient.

The first term in the above equation represents the power used to accelerate the vehicle mass, and the second and third terms represent the average power for overcoming the tire rolling resistance and aerodynamic drag.

Figure 7.6 shows the tractive effort and traction power vs. vehicle speed with a two-gear transmission. During acceleration, starting from low gear, the tractive effort follows the trace of a–b–d–e and Vb=Vb1. However, when a single-gear transmission is used, that is, only when a high gear is available, the tractive effort follows the trace of c–d–e and Vb=Vb2.

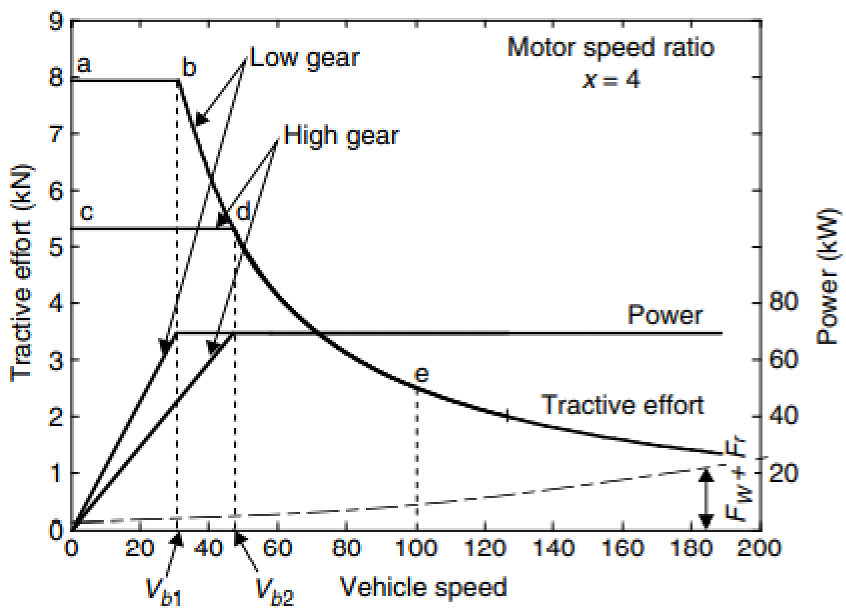


FIGURE 7.6
Speed–torque (power) characteristics of an electric motor

b)Fuel Cell System Power:

The fuel cell system must be able to supply sufficient power to support the vehicle while it drives at high constant speeds on a long trip (e.g., highway driving between cities), and to support the vehicle to overcome a mild grade at a specified speed without the help of the Peaking Power Source (PPS).

c)Design of the Power and Energy Capacity of the PPS:

1) Power Capacity of the PPS:

Based on the maximum power of the motor determined by the specified acceleration performance, and the rated power of the fuel cell system determined by the constant speed driving, the rated power of the peaking power source can be determined by

$$P_{pps} = \frac{P_{motor}}{\eta_{motor}} - P_{fc},$$

where P_{pps} is the rated power of the peaking power source, P_{motor} is the maximum motor power, η_{motor} is the efficiency of the motor drive, and P_{fc} is the rated power of the fuel cell system. The rated power of the PPS in the passenger car example is about 43 kW.

2) <u>Energy Capacity of the PPS:</u>

The PPS supplies its energy to the drive train while peaking power is needed, and restores its energy storage from regenerative braking or from the fuel cell system. The energy changes in the PPS in a driving cycle can be expressed as

$$E = \int_t (P_{pps\text{-}charge} - P_{pps\text{-}discharge})\, dt,$$

where Ppps-charge and Ppps-discharge are the charge and discharge power of the PPS, respectively. The energy changes, E, in the PPS depend on the size of the fuel cell system, vehicle control strategy, and the load power profile along with time. Figure 13.6 shows the time profiles of the vehicle speed, the power of the fuel cell system, PPS power, and energy change in the PPS Figure 13.6 indicates that the maximum energy change, ΔEmax, in PPS is quite small (about 0.1 kWh). This result implies that the PPS does not need much stored energy to support the vehicle driving in this driving cycle.

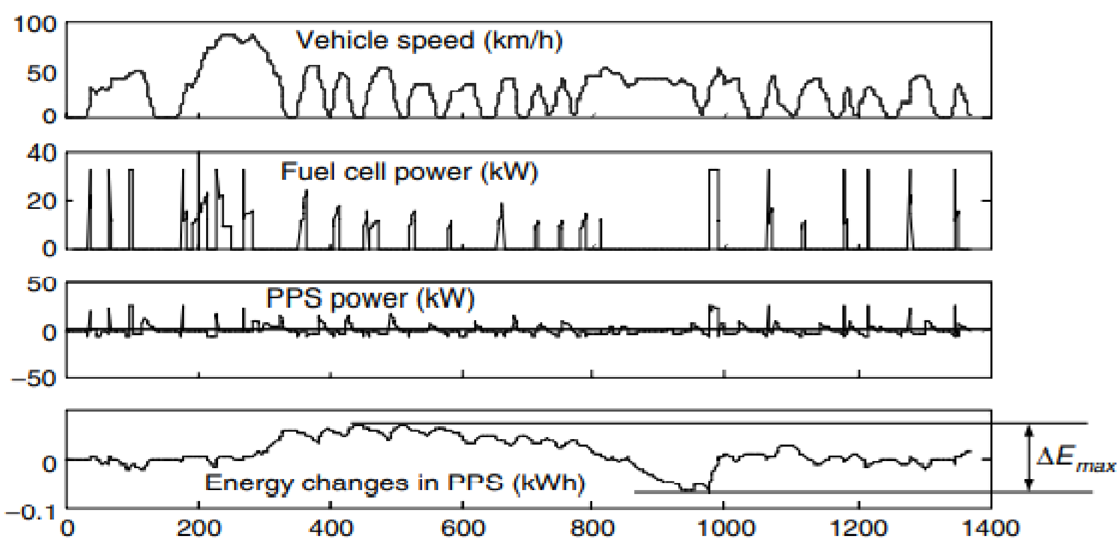


FIGURE 13.6
Vehicle speed, fuel cell power, power of the PPS, and energy changes in the PPS

Based on the maximum discharged energy in the PPS discussed above, the energy capacity of the PPS can be determined by

$$C_E = \frac{\Delta E_{max}}{C_p},$$

where CE is the total energy capacity of the PPS and Cp is the percentage of the total energy capacity that is allowed to be used, according to the characteristics of the PPS.

Fuel Cell System Characteristics:

In practice, fuel cells need auxiliaries to support their operation. The auxiliaries mainly include an air circulating pump, a coolant circulating pump, a ventilation fan, a fuel supply pump, and electrical control devices as shown in Figure 12.5. Among the auxiliaries, the air circulating pump is the largest energy consumer. The power consumed by the air circulating pump (including its drive motor) may take about 10% of the total power output of the fuel cell stack. The other auxiliaries consume much less energy compared with the air circulating pump. In a fuel cell, the air pressure on the electrode surface, P, is usually higher than the atmospheric pressure, P_o, in order to reduce the voltage drop. According to thermodynamics, the power needed to compress air from low-pressure P_o to high-pressure p with a mass flow m_{air} can be calculated by

$$P_{air\text{-}comp} = \frac{\gamma}{\gamma - 1} m_{air} RT \left[\left(\frac{p}{p_0} \right)^{(\gamma-1)/\gamma} - 1 \right] \text{(W)},$$

where γ is the ratio of specific heats of air (=1.4), R is the gas constant of air (=287.1 J/kg K), and T is the temperature at the inlet of the compressor in K. When calculating the power consumed by the air-circulating pump, the energy losses in the air pump and motor drive must be taken into account. Thus, the total power consumed is

$$P_{air\text{-}cir} = \frac{P_{air\text{-}comp}}{\eta_{ap}},$$

where η_{ap} is the efficiency of the air pump plus motor drive.

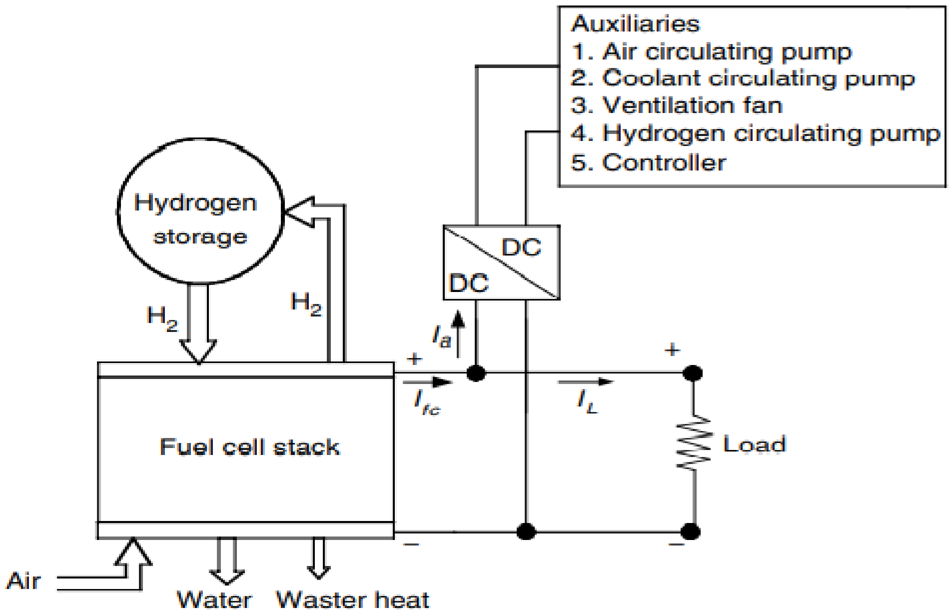


FIGURE 12.5
A hydrogen–air fuel cell system

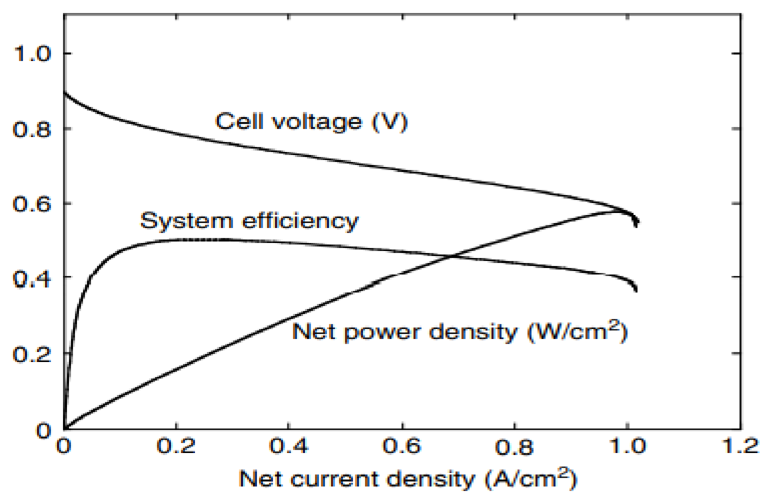


FIGURE 12.6
Cell voltage, system efficiency, and net power density varying with net current density of a hydrogen–air fuel cell

Figure 12.6 shows an example of the operation characteristics of the hydrogen–air fuel cell system, where λ=2, p/p0=3 and ηap=0.8, and the net current and net power are the current and power that flow to the load (see Figure 12.5). This figure indicates that the optimal operation region of the fuel cell system is in the middle region of the current range, say, 7 to 50% of the maximum current. A large current leads to low efficiency due to the large voltage drop in the fuel cell stack and, on the other hand, a very small current leads to low efficiency due to the increase in the percentage of the auxiliaries' energy consumption.

Example of fuel cell electric vehicle:

Proton Exchange Membrane (PEM) Fuel Cell

The proton exchange membrane (PEM) fuel cells use solid electrolytes and operate at low temperatures (around 80°C). Nafion is an example of solid polymer electrolyte. These fuel cells are also known as solid polymer membrane fuel cells. The electrical efficiency of PEM fuel cells is lower than that of the alkaline cells (about 40%). However, a rugged and simple construction makes these types of fuel cells suitable for vehicle applications. The PEM fuel cell and the AFC are currently being considered for vehicle applications. The advantage of PEM cells is that they can tolerate impurity in the fuel, as compared to pure hydrogen which is needed in alkaline fuel cells.

A fuel cell EV consists of a fuel storage system that is likely to include a fuel processor to reform raw fuel to hydrogen, a fuel cell stack and its control unit, a power-processing unit and its controller, and the propulsion unit consisting of the electric machine and drivetrain. The fuel cell has current source type characteristics, and the output voltage of a cell is low. Several fuel cells have to be stacked in series to obtain a higher voltage level, and then the output voltage needs to be boosted in order to interface with the DC/AC inverter driving an AC propulsion motor, assuming that an AC motor is used for higher power density. The block diagram of a fuel cell EV system is shown in Figure 4.3. The voltage and current values shown in the figure are arbitrary and are included to give an idea about the typical voltage ratings at different stages of the system. The power electronic interface circuit between the fuel cell and electric motor includes the DC/DC converter for voltage boost, DC/AC inverter to supply an AC motor, microprocessor/digital signal processor for controls, and battery/capacitors for energy storage. The time constant of the fuel cell stack is much slower than that of the electrical load dynamics. A battery storage system is necessary to supply the power during transient and overload conditions and also to absorb the reverse flow of energy due to regenerative braking. The battery pack voltage rating must be high in order to interface directly with the high-voltage DC link, which means that a large number of series batteries will be needed. Alternatively, a bidirectional DC/DC

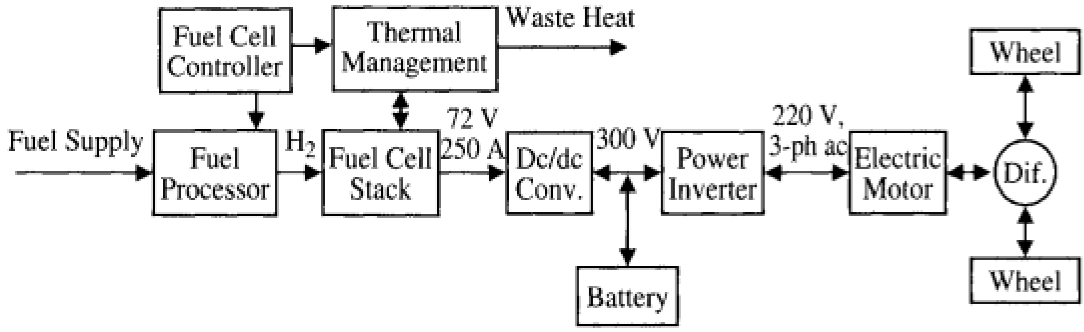


FIGURE 4.3 Fuel-cell-based EV.

converter link can interface a lower voltage battery pack and the high-voltage DC bus. The battery pack can be replaced by ultra-capacitors in a fuel cell EV, although the technology is not yet ready to replace batteries.

The by-product of the fuel cell reaction is water in the form of steam that exits the cell along with any excess hydrogen. The water vapor can be used for heating the inside of the vehicle, but the hydrogen that is vented out is a waste for the system.

Hybrid Electric Vehicle:

The term hybrid vehicle refers to a vehicle with at least two sources of power. A hybrid-electric vehicle indicates that one source of power is provided by an electric motor. The other source of motive power can come from a number of different technologies, but is typically provided by an internal combustion engine designed to run on either gasoline or diesel fuel.

HEV Configurations:

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

i. powertrain 1 alone delivers power

ii. powertrain 2 alone delivers power

iii. both powertrain 1 and 2 deliver power to load at the same time

iv. powertrain 2 obtains power from load (regenerative braking)

v. powertrain 2 obtains power from powertrain 1

vi. powertrain 2 obtains power from powertrain 1 and load at the same time

vii. powertrain 1 delivers power simultaneously to load and to powertrain 2

viii. powertrain 1 delivers power to powertrain 2 and powertrain 2 delivers power ton load

ix. powertrain 1 delivers power to load and load delivers power to powertrain 2

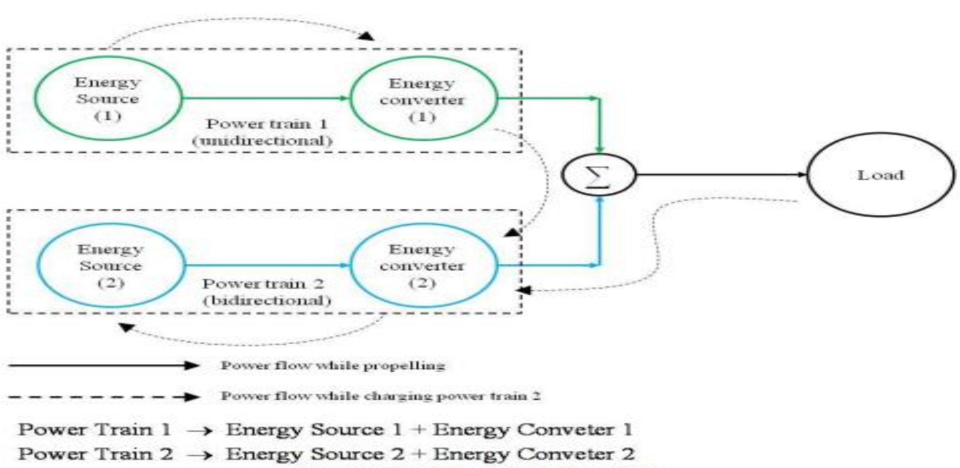


Figure 2:Generic Hybrid Drivetrain [1]

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

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

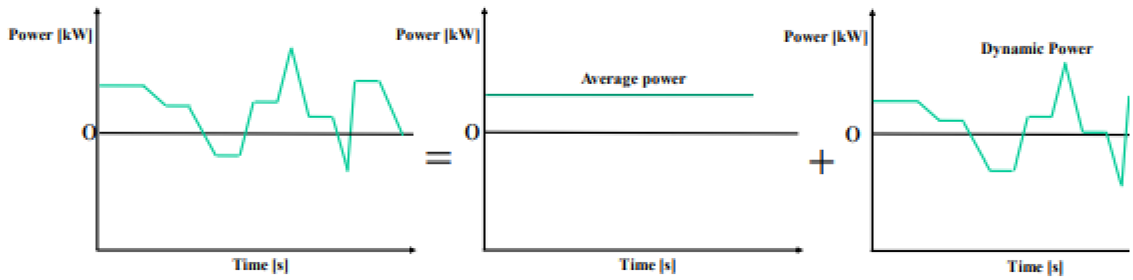


Figure 3: Load power decomposition [1]

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

- Series configuration
- Parallel configuration
- Series-parallel configuration

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

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

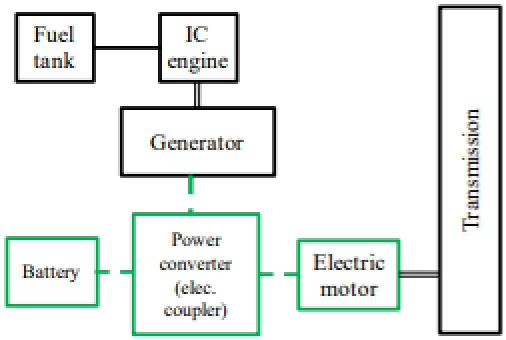


Figure 4a: Series hybrid [1]

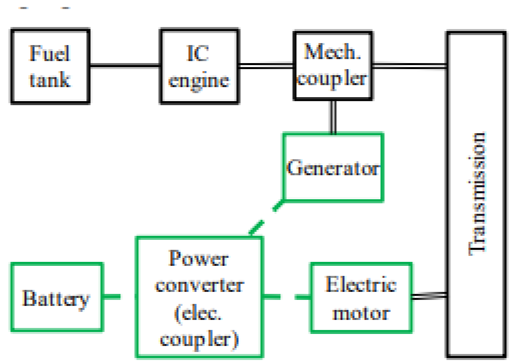


Figure 4b: Series-Parallel hybrid [1]

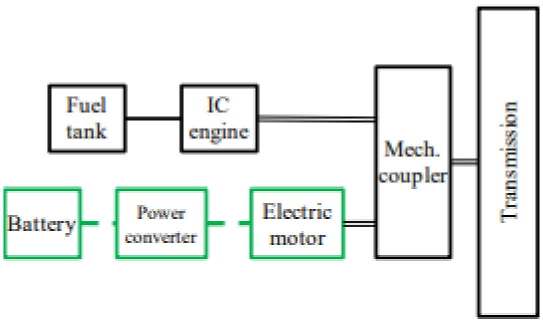


Figure 4c: Parallel hybrid [1]

<u>Series Hybrid System:</u>

A series hybrid is one in which only one energy converter can provide propulsion power. The heat engine or ICE acts as a prime mover in this configuration to drive an electric generator that delivers power to the battery or energy storage link and the propulsion motor. The component arrangement of a series HEV is shown in Figure below.

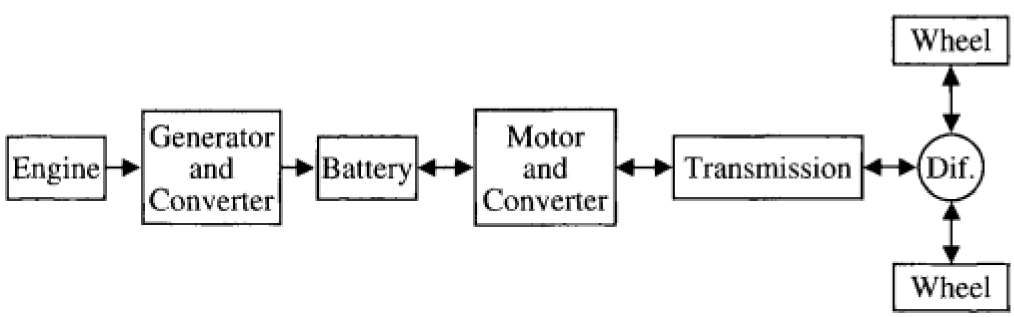


FIGURE 10.1 Series HEV drivetrain.

The advantages of a series HEV are:

1. Flexibility of location of engine-generator set

2. Simplicity of drivetrain

3. Suitability for short trips

The disadvantages of a series HEV are:

1. It needs three propulsion components: ICE, generator, and motor.

2. The motor must be designed for the maximum sustained power that the vehicle may require, such as when climbing a high grade. However, the vehicle operates below the maximum power most of the time.

3. All three drivetrain components need to be sized for maximum power for long-distance, sustained, high-speed driving. This is required, because the batteries will exhaust fairly quickly, leaving ICE to supply all the power through the generator.

Parallel Hybrid System:

A parallel hybrid is one in which more than one energy source can provide propulsion power. The heat engine and the electric motor are configured in parallel, with a mechanical coupling that blends the torque coming from the two sources. The component arrangements of a parallel hybrid are shown in Figure 10.2.

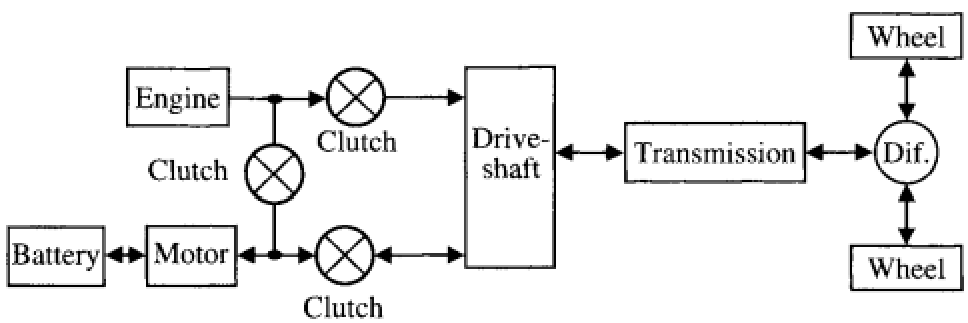


FIGURE 10.2 Parallel HEV drivetrain.

The advantages of the parallel hybrid drivetrain are:

1. It needs only two propulsion components: ICE and motor/generator. In parallel HEV, the motor can be used as the generator and vice versa.

2. A smaller engine and a smaller motor can be used to get the same performance, until batteries are depleted. For short-trip missions, both can be rated at half the maximum power to provide the total power, assuming that the batteries are never depleted. For long-distance trips, the engine may be rated for the maximum power, while the motor/ generator may still be rated to half the maximum power or even smaller

The drawbacks of parallel hybrid drivetrains are:

- The control complexity increases significantly, because power flow has to be regulated and blended from two parallel sources.
- The power blending from the ICE and the motor necessitates a complex mechanical device.

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

Series-Parallel Hybrid System:

The component arrangement of a series-parallel combination hybrid is shown in Figure 10.3. The schematic is based on the Toyota Prius hybrid design. A power split device allocates power from the ICE to the front wheels through the driveshaft and the electric generator, depending on the driving condition. The power through the generator is used to charge the batteries. The electric motor can also deliver power to the front wheels in parallel to the ICE. The inverter is bidirectional and is used to charge the batteries from the generator or to condition the power for the electric motor. For short bursts of speed, power is delivered to the driveshaft from the ICE and the electric motor. A central control unit regulates the power flow for the system using multiple feedback signals from the various sensors.

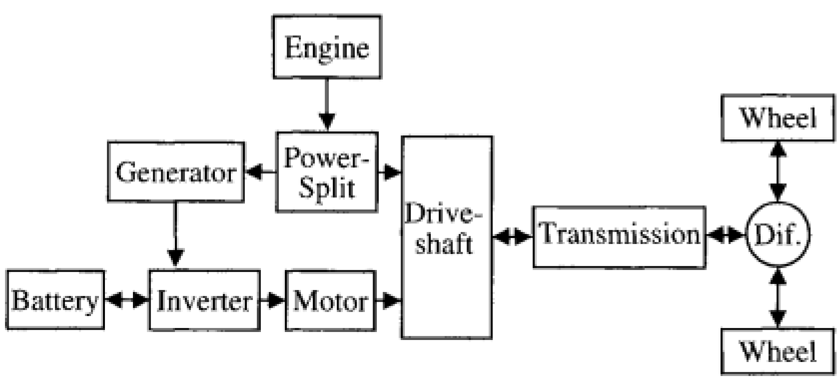
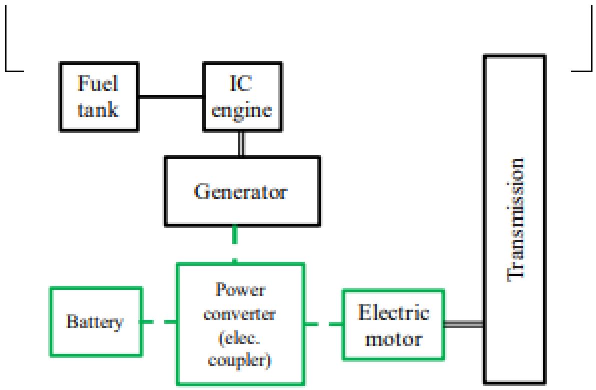
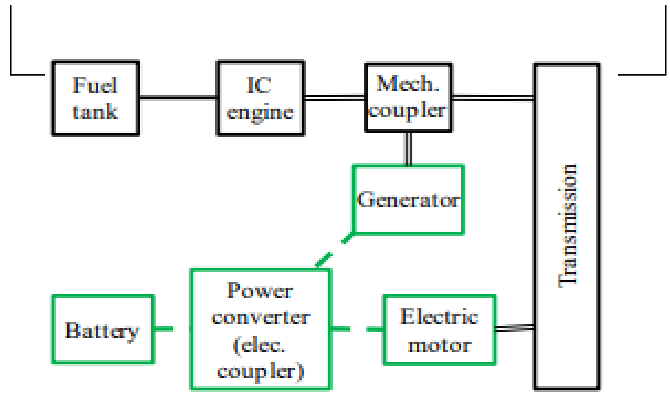


FIGURE 10.3 Series-parallel combination HEV.

Use of the ICE to charge the batteries should be minimized when maximizing efficiency. Energy is always lost while charging and discharging the battery and during the power flow through the inverter. The vehicle should be operated off its engine or battery or both, until the battery is at a minimum acceptable state of charge, say 20 to

40%. The battery should be charged from the power grid when convenient.

Comparison of series, series-parallel hybrid systems:

S.No.	**Series Hybrid System**	**Series-Parallel Hybrid System**
1		
2	Flexibility of location of engine-generator set	Complexity in the location of engine-generator set.
3	Simplicity of drivetrain	Complexity of drivetrain. The power blending from the ICE and the motor necessitates a complex mechanical device.
4	It needs three propulsion components: ICE, generator, and motor.	It needs only two propulsion components: ICE and motor/generator.
5	The motor must be designed for the maximum sustained power that the vehicle may require, such as when climbing a high grade. However, the vehicle operates below the maximum power most of the time.	The motor/ generator may still be rated to half the maximum power or even smaller.
6	All three drivetrain components need to be sized for maximum power for long-distance, sustained, high-speed driving.	A smaller engine and a smaller motor can be used to get the same performance, until batteries are depleted.
7	Example: Cadillac ELR	Example: Toyota Prius

Brake specific fuel consumption:

Brake specific fuel consumption is the ratio of a mass flow rate of the fuel supplied to the engine to the brake power obtained at a crankshaft and it indicates how efficiently the fuel is used to produce brake power.

$$\text{BSFC} = \frac{\text{Fuel mass flow rate}(\dot{m})}{\text{Brake power}(BP)}$$

Where Brake power is power at the crankshaft which is given by,

$$\text{BP} = \frac{2\pi NT}{60}$$

Where,

T = Torque at the crankshaft

N = RPM of the crankshaft

The SI unit of brake specific fuel consumption is Kg/kWh.

The BSFC says how effectively the amount of fuel gets converted into brake power. Thus on this basis, it is easy to compare the efficiencies of the different engines irrespective of the other parameters like engine capacity, engine size, number of cylinders, etc.

The lowest value of the BSFC indicates that the engine is more efficient and if we increase the value of BSFC consequently the efficiency of the engine decreases.

The importance of BSFC are as follows:-

1] The BSFC says how efficiency the particular fuel gets converted into the brake power.
The lower value of BSFC indicates that the engine requires less amount of fuel for the generation of the unit amount of power.

2] It is helpful to compare different automobiles based on their ability to convert fuel into brake power.