04

H_2 fuel cell for transport

High voltage components

Index

Objectives

- To understand the function of car batteries: lead, lithium-ion (Li-ion) and nickel-metal hydride (Ni-MH).
- To be aware of the battery management issue on the basis of the battery management system (BMS) and recognise the relevance of battery thermal management.
- To be aware of the risks of fire in the case of poorly managed batteries.
- To understand the operating principle of a DC/DC converter enabling the 12 V auxiliary battery to be recharged.
- To understand the operating principle of a buck-boost type of DC/DC converter for connecting the fuel cell and HV battery pack.
- To understand the operating principle of a DC/AC converter to power an electric motor.
- To understand the operating principle of braking energy recovery and the role of the diode bridge of the converter.
- To understand the electrical signals supplying or outputted by the convertors, knowing where and how to measure them.
- To know how to recognise a properly operating converter.
- To understand the operating principle of synchronous and asynchronous electric machines.

Introduction

Transport vehicle technicians have always been mechanics. Their habits and attitudes stem from a mechanics-based approach, their way of working involves discovering and solving problems. This approach is no longer possible, because developments in vehicle technology have introduced high-voltage electricity into the powertrain; first via hybrid petrol/electric vehicles, followed by electric vehicles and, lastly the hybrid fuel cell/battery vehicles.

While there is no loss of performance, there are fewer and fewer moving parts matched by ever-increasing control, command and power electronics in vehicles. The profession is therefore set to shift from a "mechanical operation observation" role to an "electric operation measurement" in order to deduce the operating condition: nominal, degraded or immobilised performance.

In order to retain the performance, users are accustomed to an operating power equivalent to several tens of kilowatts. In order to keep the current within an acceptable range, operating from a high-voltage perspective is a must. For example, a capacity of 100 kW will be equal to:

- In DC: 300 Volts and 333 Amps
- In AC after boost converter: 650 Volts and 110 Amps

As a result of these high levels of current, it is impossible to work with lower voltages. **It is therefore most important or even crucial to ensure compliance with the relevant operating procedures, safety regulations and the use of protective equipment.**

A stage-by-stage description of how the high-voltage equipment chain operates will be given from the fuel cell to the traction motor. This will cover the following:

- Fuel cell
- Boost converter
- High-voltage battery
- High-voltage bus
- 12 V battery charger
- DC/AC converter
- Electric machine

1.1. Teaser presenting unit 4

1.2. High-voltage batteries

1.2.1. Types of batteries

Lead acid

Used for a long time to power 12 V car accessories, this type of battery operates according to the redox principle. One electrode is made of lead and the other of lead oxide, while the electrolyte is made of sulphuric acid. They are extremely robust and do not require any specific electronic management. The nominal voltage of a cell is 2.1 V. The sole limitation is a **low specific energy** not usable for a traction application.

Nickel-metal hydride (Ni-MH)

In a nickel metal hydride battery, the anode is composed of hydrogen absorbed in a metal hydride (MH), the cathode is made of nickel hydroxide ($Ni(OH)_2$) and the electrolyte is made of potassium hydroxide (KOH). It operates according to the oxidation-reduction principle. The nominal voltage of a cell is 1.2 V.

Lithium (Li-ion and LiPO)

Lithium-ion batteries use a lithium alloy for the positive electrode. The negative electrode is generally made of carbon having absorbed lithium ions. The electrolyte is a lithium salt in gel form. In the case of lithium-polymer batteries, the electrolyte is a solid polymer. The nominal voltage of a cell can vary from 3.5 V to 3.75 V depending on the type of alloy used for the positive electrode. The operating principle is based on the ion exchange between the electrodes. This is illustrated in Figure 1 for discharging and charging.

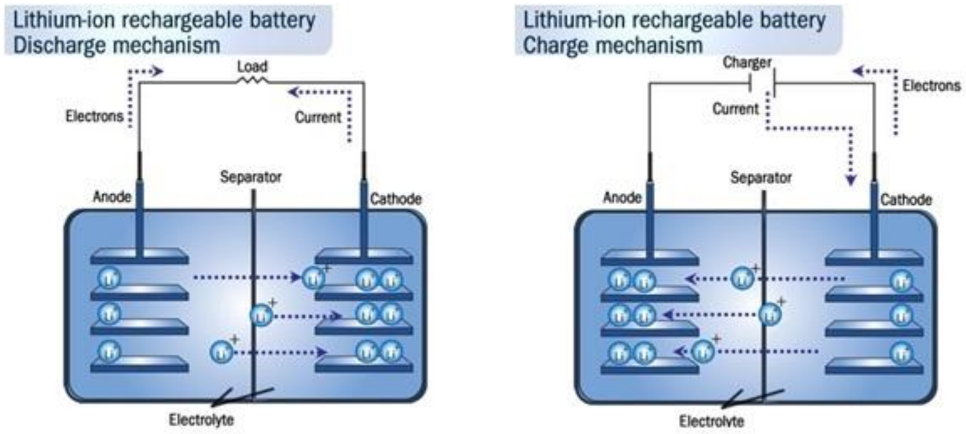


Figure 1 Principle of the Li-ion battery.

These latter two technologies have replaced lead batteries due to their **high specific power** (kW/kg) and high **specific energy** (kWh/kg). Ni-MH batteries are easier to manage but Li-ion batteries offer a slightly higher performance:

- lower self-discharge
- higher per-cell voltage
- higher load current

The present trend is for Ni-MH batteries to be used for standard hybrid vehicles and Li-ion batteries for plug-in vehicles. The battery will consist of elementary cells connected in series and in parallel:

- in series to obtain the required voltage expressed in Volts (V)
- in parallel to obtain the required capacity expressed in Amps per hour (Ah)

In practice, the high-voltage battery will be placed in a metal protective container, as shown in Figure 2.

Figure 2 Protected high-voltage battery (source Autoform).

<u>Supercapacitors</u>

These are specific medium-capacity capacitators between the electrolytic capacitators and batteries. They provide fairly low but almost instantaneous storage of energy that is released very quickly. They are thus capable of significantly increasing the available power for a short time. They act as energy buffers. They may be used by themselves or associated with a battery or a fuel cell. A typical application is the KERS (Kinetic Energy Recovery System).

In summary, Table 1 compares the main features of the storage possibilities available.

Table 1 Properties of electrical energy storage methods.

Properties	Fuel cell	Lead	Ni-MH	Li-ion	Super capacitor
Cell voltage	0.8	2.1	1.2	3.5	2.7
Specific power (W/kg)	200 - 2000	30	300	300	**3000**
Specific energy (Wh/kg)	**200 - 2000**	30	**100 - 200**	100 - 200	4 – 5
Need of BMS	yes	no	yes	yes	no

1.2.2. Battery management systems (BMS)

It is known by now that a battery is an assembly of elementary cells. We also know that a cell may not be subject to a voltage overload or high temperatures as this could cause a fire. For example, a Li-ion battery cell must have its operating point between 2 and 4 V and between -10 °C and 100 °C. A Ni-MH cell should never exceed a voltage of 1.6 V and a temperature of 100 °C. In the context of low voltages and low temperatures, there is a risk of impairing the battery's performance.

This type of battery therefore has to be able to rely on a BMS.

Another problem that arises is that the state of charge of the ~200 cells that form the battery is not the same, yet the management system will interrupt the operation of the entire battery if one single cell departs from the nominal conditions.

The BMS will therefore ultimately have five key roles to play:

- achieve uniformity in the voltage of all the cells
- monitor the temperature of the cells and activate the ventilation if necessary
- measure the voltage of each cell and stop the charging or discharging of the battery
- check the insulation of the battery with the chassis
- measure the energy entering and leaving the battery in order to be able to display a level gauge to the user

Three methods are available to balance the battery cell voltage level: resistive, capacitive and inductive. Figure 3 shows the capacitive method. In the light of unbalanced cells, whose charge levels are shown on the left-hand side of the figure, the right-hand system actuated by transistors allows for the energy of the busiest cells to be transferred to other cells. Once the cells are balanced, the battery capacity will be at its optimum, as the BMS will take into account all of the cells rather than just one in order to make a decision.

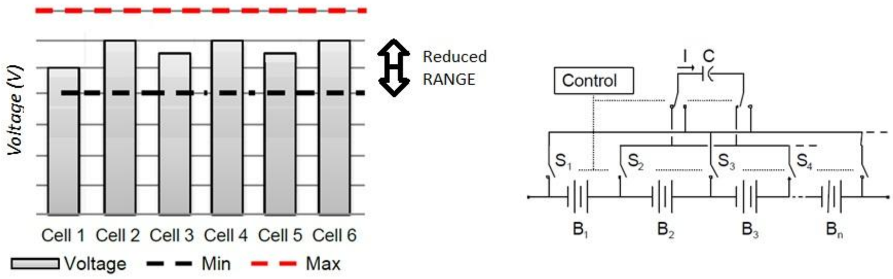


Figure 3 Cell imbalance and role of the BMS.

Figure 4 shows the content of the battery box, featuring the assembly of cells, the control unit (BMS) and the fan. The temperature sensors placed on the battery can be seen. Note that for safety reasons, the battery cooling system has to be able to operate when the vehicle has stopped, or even parked.

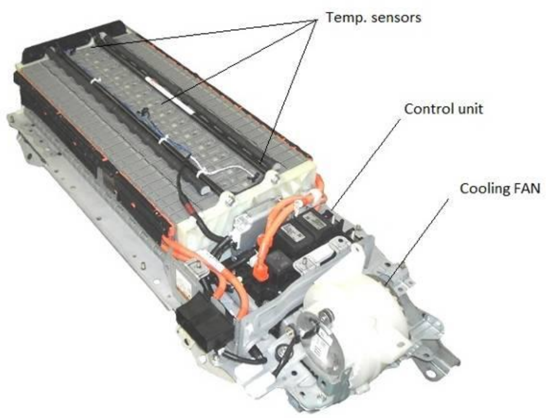


Figure 4 Temperature monitoring (source Toyota & Educam).

1.3. DC / DC converters

1.3.1. Boost converter for Fuel Cell & HV Battery

A fuel cell vehicle is a hybrid vehicle in the sense that it features a battery and sometimes supercapacitors in order to increase the instantaneous power available and be able to recover the braking energy. Reactions in the fuel cell cannot be reversed and it does not offer a means of recovering the electrical energy generated during braking. It is also protected by a diode to avoid any inward current. The operation of a sound hybrid strategy is dependent upon these two sources of energy interacting effectively. Towards this end, we use a DC/DC negative booster or positive booster converter because the voltages in the cell, battery and at the output are not the same. An example of a converter fulfilling this role is a "buck-boost". Its operating principle is quite straightforward.

Figure 5 shows a Q1 transistor supplied by a square wave signal, also called pulse-pause, with an L1 inductance to earth. This transistor will work like a switch that will open and close at a high frequency. This will store energy in L1 during the transistor on-state then restore the energy to capacity and load during the transistor off state. Adjusting the cyclic ratio of the square wave signal can vary the output voltage.

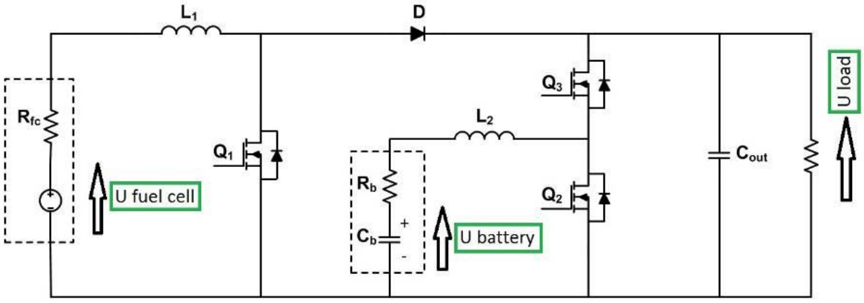


Figure 5 Diagram of a buck-boost for FC and battery.

Still in reference to Figure 5, a second embedded converter allows a high-voltage battery to be connected as well via Q2 and L2 and to obtain an output voltage suitable for the motor system. According to this diagram, several operating methods are possible:

- The current drawn by the motor is derived from the fuel cell and the battery (high demand)
- The fuel cell supplies the motor and recharges the battery (low demand)
- The electric machine operates as an alternator and recharges the battery (braking)

In the case of the Mirai, Toyota has announced a fuel cell voltage of ~360 V, a battery of ~240 V and an output voltage of ~650 V to supply the motor inverter. The cell and booster are shown below in Figure 6.

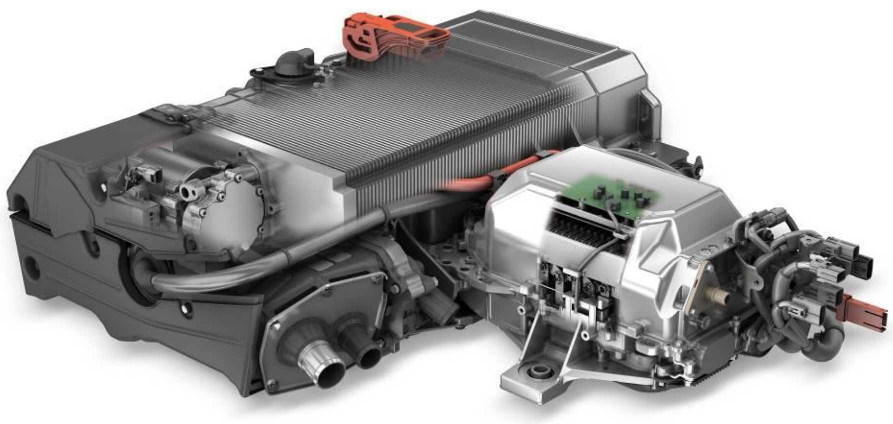


Figure 6 Fuel cell and booster of the Toyota Mirai (source Toyota).

1.3.2. DC/DC converter as auxiliary battery charger

Electric vehicles have a 12 V battery as certain accessories require this and the control electronics can therefore be supplied prior to the commissioning of the main energy source. This 12 V battery is normally permanently charged by an alternator driven by a combustion engine. An electric or hybrid car no longer has an alternator, so a DC/DC converter is used instead. This is illustrated below in Figure 7.

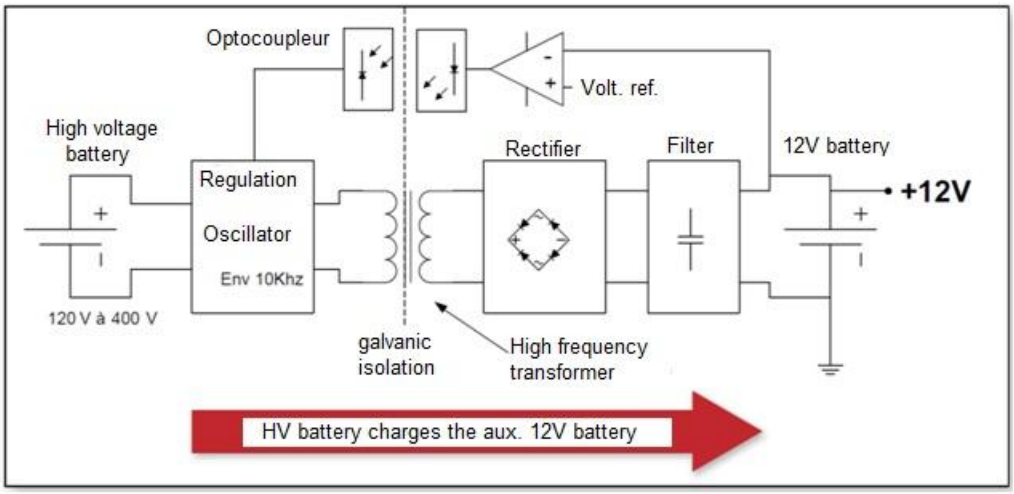


Figure 7 Diagram of the DC/DC converter or 12 V charger (source Toyota).

As a safety precaution, there is a galvanic isolation between the high and low voltage. The direct high voltage is converted into alternating voltage prior to supplying the primary coil of a transformer. The alternative voltage of lower voltage obtained at the scondary coil is then rectified and filtered (~13.5 V DC) before connection to the auxiliary battery.

1.4. DC/AC inverters

1.4.1. Motor mode

On the grounds of performance, electric machines found in practice are 3-phase alternating current (AC) because, if direct current (DC) machines are easier to control they are not reliable. Effectively, they use brushes which are submitted to friction, wear and sparks. This is not aceptable, particularly for high power motors.

As the choice of a maintenance free AC electric machine is obvious, this involves converting a direct current (DC) from a battery into 3-phase alternating current (AC). This operation is resolved quite easily via an inverter as illustrated in the top right in Figures 8 and 9. The architecture of the circuit is a Graetz bridge which is made up of transistors when the current circulates from the battery to the motor. As we will see later, it is made of diodes when the current circulates from the motor/generator to the battery.

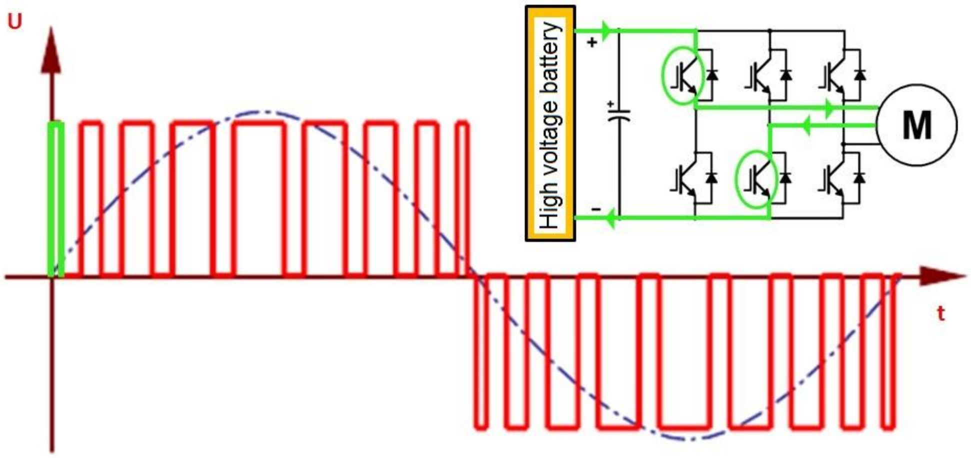


Figure 8 Positive half wave of an AC signal.

In the case of the two higher motor phases, Figure 8 shows that the chopped control of the 2 “surrounded” transistors on first and second arms will permit the generation of the positive half wave of the electric voltage signal. The main idea is to send a square wave signal or "pulse-pause" in varied widths with the widest pulse positioned in the middle and the narrowest positioned on the edges. Consequently, a medium voltage is obtained following a sinusoidal profile similar to the one illustrated by the blue dotted line.

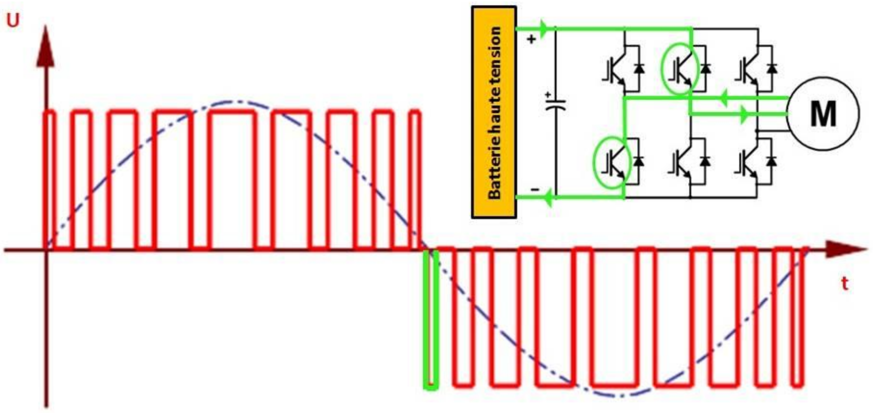


Figure 9 Negative half wave of an AC signal.

Next Figure 9 shows that the chopped control of the 2 opposite transistors **on the same arms of the bridge** will allow the negative half wave of the electric voltage signal to be generated.

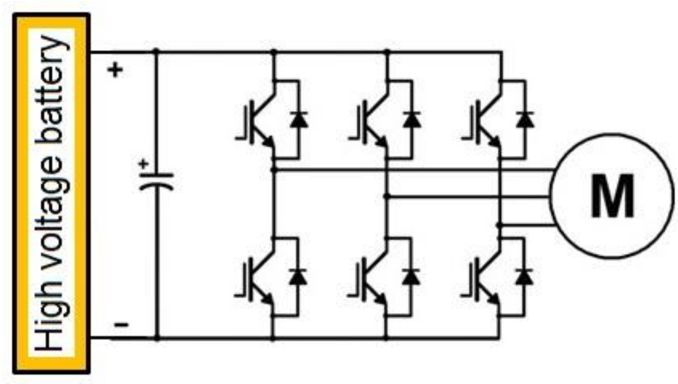
In both cases, **a mechanical inertia will receive the average of the chopped signal** and, **thus**, **a sinusoid**. In the case of an electric machine, it will be equivalent to the blue dotted signal, which also illustrates the current signal.

The control electronics will then provide the same function for the 2 other bridge arm combinations, 1 - 3 and 2 - 3, to supply the 3 machine phases with three 1/3 time-shifted half-wave signals. These will be illustrated further in Figure 10.

Lastly, the motor speed control will be undertaken as a result of varying the frequency of the signals while keeping the Voltage/frequency ratio (U/f) constant to operate at constant torque.

1.4.2. Regenerative mode

During vehicle braking, the inertia rotates the electric machine which becomes an AC generator. The voltage polarity changes at each cycle for the 3 connected phases. The current will flow from the machine to the battery by means of the diode bridge placed in parallel on each transistor. These diodes are required because the transistors are unidirectional and allow current to flow solely from the battery to the electric motor. The role of the diode bridge is to rectify each half wave from each phase then use the capacitator to filter the signal. This operation serves to supply the battery as illustrated by the following animation.



Animation 1 Function of the diode bridge.

1.5. Electric machines & transmission

Electric machines include a stator containing angularly offset coils: 3 coils will be offset 120°, 6 coils 60°, 9 coils 40°, and so on. The coils are supplied successively by the three phases from the inverter. They will create a magnetic field rotating at the speed set by the frequency of the electric signals, the synchronous speed. Figure 10 below shows an example of a stator and, on the right, an example of 3 coil distribution. The black arrow on the diagram represents the magnetic fields resulting at a specific time from the combined effect of 3 electric signals.

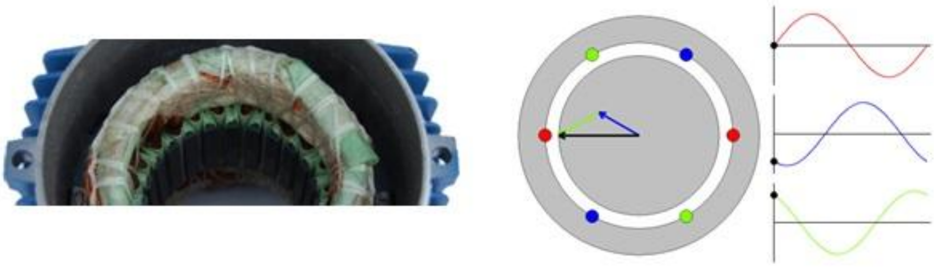


Figure 10 View and diagram of the stator of a 3-phase AC machine.

1.5.1. Synchronous machines

The rotating magnet field will rotate a rotor.

The rotor of a **synchronous machine**, as illustrated in Figure 11, comprises permanent magnets that will align with the magnetic field induced by the coils and **rotate at the same speed**, hence the name synchronous machine.

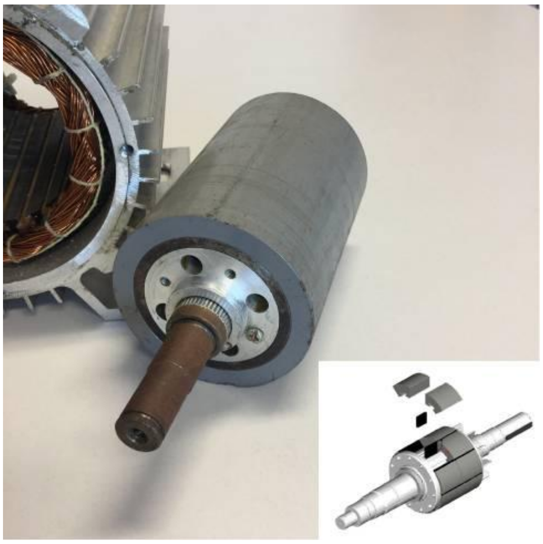


Figure 11 View and diagram of the magnets of a synchronous machine.

Often favoured by manufacturers, because it is directly reversible as this type of machine operates as an alternator. When the machine rotor is rotated by an external force the coils then produce an AC 3-phase current. However, the machine has two drawbacks:

- First of all the cost and availability of materials for permanent magnets such as neodymium. Manufacturers are therefore prepared to replace them with wound rotors if need be.
- Second, the problem of rotor stall when the torque required is too high, so that the magnetic field rotates around a rotator at a standstill. In order to overcome this inconvenience and provide a high drive torque, sensors provide the

measurement of the position relative to the magnetic field and stator. Amongst the various technologies, Figure 12 illustrates the Hall effect sensors placed on the 3 adjacent coils of the stator.

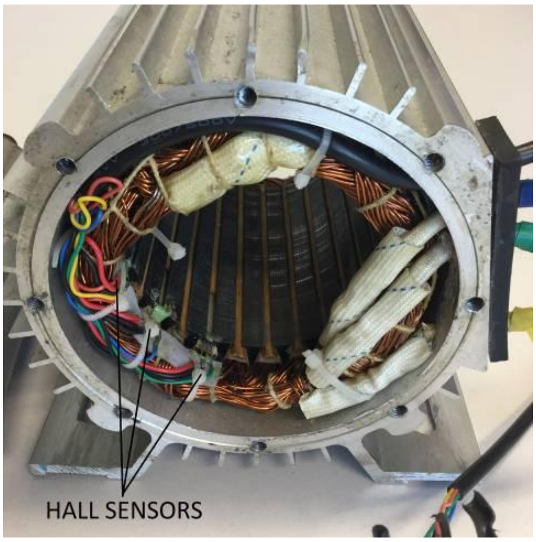


Figure 12 View of the Hall effect sensors placed in the stator.

These sensors will communicate with the inverter, whereupon the magnetic field will "await" the rotor and maintain the orthogonality between the magnetic field and electric current at all times. In this case, 5 control wires should be connected to the inverter, 3 "Hall" signals and 2 supply wires. Another technology involves measuring the signals from unpowered coils.

1.5.2. Asynchronous machines

The rotating magnet field will rotate a rotor.

The magnetic field of an **asynchronous machine**, as illustrated in Figure 13, comprises short-circuited conductor bars. A shifting magnetic field will create an electric current in a short-circuit bar. The current itself will create a magnetic field which will oppose any change to the current that produced it, according to Lenz's law. This opposition will create a force and **rotate the rotor at a speed lower than that of the magnetic field.** It will be lower, because of the need to maintain a relative speed at all times between the rotor and magnetic field. This speed difference is called slip.

Figure 13 View of the rotor of an asynchronous machine.

This machine is not naturally reversible. To recover braking energy, what is needed is an inverter able to send a signal with a lower frequency than the one corresponding to the rotation speed, thereby allowing the current to change direction.

1.5.3. Transmission


Figure 14 View of a transmission (source Honda).

The electric vehicle transmission system has become very straightforward. The electric machine is built in a casing, which also contains an axle ratio and differential. Next comes the cardan joints, hubs and wheels. Most vehicles no longer require a gearbox. An example of direct transmission is illustrated below in Figure 14.

1.6. Low voltage battery & accessories

An electric vehicle invariably includes a 12 V battery because some accessories use this voltage. Moreover, the availability of a highly reliable lead acid battery makes it possible to check the system status prior to the high-voltage start-up.

The 12 V accessories include lights, wiper, washer, power-operated windows, infotainment, cigarette lighter, power-operated seats and most importantly, the control unit used in particular for supplying the relays with high-voltage sources. **It is therefore obvious that if the 12 V battery fails, the vehicle cannot start.**

Some other items of equipment are more energy-intensive and are driven by a belt on an internal combustion engine. With a standard electric vehicle the passenger compartment is heated via a heating resistance powered by the high-voltage bus. In the case of a fuel cell, passenger compartment heat is derived from the cell cooling circuit via an exchanger. This brings us, finally, to accessories driven by an electric motor supplied by the high-voltage bus, such as:

- the conditioning compressor
- the power steering pump
- the cooling circuit water pump
- the fuel cell air compressor
- the fuel cell hydrogen pump
- the humidifier water pump (optional)

Summary

This unit showed us that a fuel cell vehicle is in fact a hybrid vehicle carrying two sources of energy on board: a fuel cell and a high-voltage battery. **It is in a way a hydrogen-electric hybrid**. Consequently, it is no surprise to see a DC/DC power converter among the components which enables the fuel cell and high-voltage battery to interact according to three main modes:

- The battery can back up the fuel cell in the event of a high motor demand.
- The fuel cell may recharge the battery if necessary in the case of low motor demand.
- The electric motor may become a generator in the event of braking, thereby recovering the energy for recharging the battery.

Apart from this special characteristic, electric components seen in a fuel cell vehicle are the same as those already seen in hybrid petrol/electric vehicles and in electric vehicles

There are fuel cells able to convert hydrogen into electricity, with the voltage generated depending on the number of cells in series – between 300 V and 400 V for a car.

There is a NiMH or possibly a Li-ion battery whose voltage is compatible with the fuel cell of roughly 240 V.

There is a DC/DC converter allowing for a hybrid cell-battery operation and another DC/DC converter lowering the voltage of the high-voltage battery to 14 V to act as a charger for the standard 12 V battery supplying certain accessories.

Next is a reversible DC/AC converter for supplying an electric motor in alternating current 3-phase. This inverter is provided in parallel with the diode bridge for rectifying the alternating current to direct current, to allow the electric machine to operate as an alternator during the vehicle energy recovery phases: lowering, deceleration and braking.

Lastly, there is the electric machine in its most efficient form. This is a 3-phase synchronous machine which is comprised of a rotor with permanent neodymium magnets or an asynchronous machine with a cage rotor.