UNIT-3

ENERGY STORAGE

Introduction to Energy Storage Requirements in Hybrid and Electric Vehicles

Energy storage systems for electric vehicles Energy storage systems (ESSs) are becoming essential in power markets to increase the use of renewable energy, reduce CO2emission, and define the smart grid technology concept ESS has an important effect on overall electric systems; it provides continuous and flexible power supply to maintain and to enhance power as a result of congestion and interruption of transmission line for excessive demand.

In addition, an ESS ensures reliable services for consumers during power crises due to natural disasters, as well as lessens the prices of electricity to support the peak demand by storing energy during off-peak hours at low cost.

During the past decades, renewable energy has been contributing to off-grid power consumers with ESSs. In that sense, EVs are growing technologies with ESS as a substitute for fossil fuels, where energy resources come from renewable energy technologies. EVs are utilized to discourage the use of fossil fuels and reduce CO2.

Hence, high-performance ESSs are necessary to power EVs. To meet some requisites of EVs, ESSs are utilized in combination to provide high discharge time with reliability. The drive train architectures of EVs it present a BEV drive system and a series-parallel full HEV, respectively.

➢ **Classification of ESS system**

The classification of ESS systems is determined with the use of energy in a specific form. ESS is classified into mechanical, electro-chemical, chemical, electrical, thermal, and hybrid [30]. These systems are classified into various types according to their formations and composition materials .it presents the classification of ESS in detail, where the common ESSs for EV application are boxed in gray. Flywheel, secondary electro chemical batteries, FCs, UCs, super cool-ducting magnetic coils, and hybrid ESSs are commonly used in empowering application

➢ **Mechanical storage system**

Mechanical storage systems (MSSs) are commonly used to produce electricity throughout the world. Three MSSs are pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage (FES). The most popular MSS is PHS, which are used in pumped hydroelectric power plants. Reserved water of high head issued and pumped to a power turbine with a generator to produce electricity. This storage system contributes approximately 99% of the world electric storage capacity, which is around 3% of the capacity of global electricity generation.

In CAES, compressed air is mixed with natural gas, expanded, and further converted into modified gas to feed to a gas turbine shafted with a generator to produce electricity. The isothermal, adiabatic, and diabetic storage systems are considered to implement CAES. CAES is applicable for large-capacity electricity production. FES is explained below.

➢ **Flywheel energy storage**

Flywheel energy storage (FES) systems are suitable for the application of EVs and power systems because of advances in power electronics and material engineering. The efficiency and rated power of FES fall within the range of 90–95% and 0–50 MW, respectively. The flywheel comprises a rotating cylindrical body in a chamber, coupled bearings, and energy transmission device, i.e., generator/motor together mounted with a common shaft. The energy maintained by the constantly rotating flywheel is converted to Classification of energy storage systems (ESS) according to their energy formations and composition materials.M.A. Hanna et al. Renewable and Sustainable Energy Reviews

➢ **Electro chemical storage systems**

All conventional rechargeable batteries are under electrochemical storage systems (EcSSs) . Particularly, flow batteries (FBs) and secondary rechargeable batteries are EcSSs. In EcSSs, energy is transformed from electrical to chemical energy and vice versa through reversible process with energy efficiency and low physical changes. However, chemical reaction may reduce cell life and energy .These types of batteries have the dual function of storing and releasing electrical energy by changing the charge and discharge phases with no harmful emission and little maintenance

➢ **Secondary (rechargeable) batteries**

SBs dominate the market for portable energy storage devices for Motor Generator Flywheel PowerConverter, PowerSource, PowerSink, Power Converter Motor /Generator Flywheel,Energy Flow, Power Converter(AC -AC)Power Source/Sink(a) (b)(AC -AC)(AC -AC)Energy Flow,energy Flow. Basic FES system structures: (a) two-machine system and (b) one-machine system with bidirectional energy flow Vanadium redox flow battery system.

Battery Cell Used In EV And HEV Vehicles

Types of battery cell used for EV And HEV Vehicles

- ➢ Lead-acid (Pb-acid)
- ➢ Nickel-cadmium (NiCd)
- ➢ Nickel-metal-hydride (NiMH)
- ➢ Lithium-ion (Li-ion)

➢ Lithium-polymer (Li-poly)

➢ Sodium-sulfur (NaS)

➢ Zinc-air (Zn-Air)

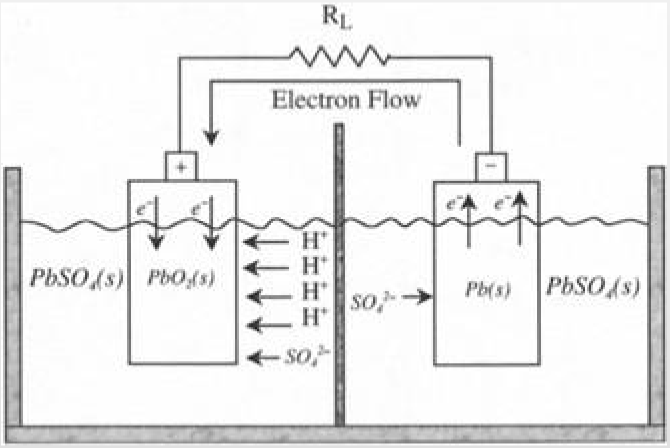
➢ Nickel Metal Hybride Batteries

Battery based energy storage and its analysis

Electro chemical Process During The Discharge And Charge Of Lead-Acid Battery Cell.

➢ **Cell Discharge Operation**

In the cell discharge operation electrons are consumed at the positive electrode, the supply of which comes from the negative electrode. The current flow is, therefore, out of the positive electrode into the motor-load, with the battery acting as the source.



Cell Discharging Operation

The positive electrode equation is given by:

$$PbO_2(s) + 4H^+(aq) + SO_4^{2-}(aq) + 2e \rightarrow PbSO_4 + 2H_2O(l)$$

A highly porous structure is used for the positive electrode to increase the PbO2(s)/electrolyte contact area, which is about 50 to 150 m2 per Ah of battery capacity.

The negative electrode equation during cell discharge is:

$$Pb(s) + SO_4^{2-}(aq) \rightarrow PbSO_4 + 2e$$

This results in higher current densities, as PbO2 is converted to PbSO4(s). As discharge proceeds, the internal resistance of the cell rises due to PbSO4 formation and decreases the electrolyte conductivity as H2SO4 is consumed. PbSO4(s) deposited on either electrode in a dense, fine-grain form can lead to sulfatation. The discharge reaction is largely inhibited by the buildup of PbSO4, which reduces cell capacity significantly from the theoretical capacity.

The negative electrode equation during cell discharge is:

$$Pb(s) + SO_4^{2-}(aq) \rightarrow PbSO_4 + 2e$$

The electrons are released at the negative electrode during discharge operation. The production of PbSO4(s) can degrade battery performance by making the negative electrode more passive.

- **Cell Charge Operation**

The cell charge operation is the reverse of the cell discharge operation. During cell charging, lead sulfate is converted back to the reactant states of lead and lead oxide. The electrons are consumed from the external source at the negative electrode, while the positive electrode releases the electrons. The current flows into the positive electrode from the external source, thereby delivering electrical energy into the cell, where it gets converted into chemical energy.
The chemical reaction at the positive electrode during cell charging is:

$$PbSO_4(s) + 2H_2O(l) \rightarrow PbO_2(s) + 4H^+(aq) + SO_4^{2-}(aq) + 2e$$

The chemical reaction at the negative electrode during cell charging is:

$$PbSO_4(s) + 2e \rightarrow Pb(s) + SO_4^{2-}(aq)$$

The overall chemical reaction during cell charging is:

$$2PbSO_4(s) + 2H_2O(l) \rightarrow Pb(s) + PbO_2(s) + 2H_2SO_4(aq)$$

Conventionally, lead-acid batteries are of flooded-electrolyte cells, where free acid covers all the plates. This imposes the constraint of maintaining an upright position for the battery, which is difficult in certain portable situations.
Efforts in developing hermetically sealed batteries faced the problem of buildup of an explosive mixture of hydrogen and oxygen on approaching the top-of-charge or overcharge condition during cell recharging.
The problem is addressed in the valve-regulated-lead-acid (VRLA) batteries by providing a path for the oxygen, liberated at the positive electrode, to reach the negative electrode, where it recombines to form lead-sulfate.

Electro chemical process of different types Nickel-based Batteries.

- **Nickel/Iron System**

The nickel/iron system was commercialized during the early years of the 20th century. Applications included fork-lift trucks, mine locomotives, shuttle vehicles, railway locomotives, and motorized hand-trucks.1 The system comprises a nickel (III) hydroxy-oxide (NiOOH) positive electrode and a metallic iron negative electrode. The electrolyte is a concentrated solution of potassium hydroxide (typically 240 g/l) containing lithium hydroxide (50 g/l). The cell reaction is given in Table 10.1 and its nominal open-circuit voltage is 1.37 V. Nickel/iron batteries suffer from gassing, corrosion, and self-discharge problems. These problems have been partially or totally solved in prototypes that have yet to reach the market. These batteries are

complex due to the need to maintain the water level and the safe disposal of the hydrogen and oxygen released during the discharge process.
Nickel–iron batteries also suffer from low temperatures, although less than lead-acid batteries. Finally, the cost of nickel is significantly higher than that of lead. Their greatest advantages are high power density compared with lead-acid batteries, and a capability of withstanding 2000 deep discharges.

- **Nickel/Cadmium Battery**

  The nickel/cadmium system uses the same positive electrodes and electrolyte as the nickel/iron system, in combination with metallic cadmium negative electrodes. The cell reaction is given in Table 10.1 and its nominal open-circuit voltage is 1.3 V. Historically, the development of the battery has coincided with that of nickel/iron and they have a similar performance.
  Nickel/cadmium technology has seen enormous technical improvement because of the advantages of high specific power (over 220 W/kg), long cycle life (up to 2000 cycles), a high tolerance of electric and mechanical abuse, a small voltage drop over a wide range of discharge currents, rapid charge capability (about 40 to 80% in 18 min), wide operating temperature (-40 to 85°C), low self-discharge rate (<0.5% per day), excellent long-term storage due to negligible corrosion, and availability in a variety of size designs. However, the nickel/cadmium battery has some disadvantages, including high initial cost, relatively low cell voltage, and the carcinogenicity and environmental hazard of cadmium.
  The nickel/cadmium battery can be generally divided into two major categories, namely the vented and sealed types. The vented type consists of many alternatives. The vented sintered-plate is a more recent development, which has a high specific energy but is more expensive. It is characterized by a flat discharge voltage profile, and superior high current rate and low-temperature performance. A sealed nickel/cadmium battery incorporates a specific cell design feature to prevent a build-up of pressure in the cell caused by gassing during overcharge. As a result, the battery requires no maintenance.
  The major manufacturers of the nickel/cadmium battery for EV and HEV allocation are SAFT and VARTA. Recent EVs powered by the nickel/cadmium battery have included the Chrysler TE Van, Citroën AX, Mazda Roadster, Mitsubishi EV, Peugeot 106, and Renault Clio.

- **Nickel-Metal-Hydride (Ni-MH) Battery**

  The Nickel-metal hydride battery has been on the market since 1992. Its characteristics are similar to those of the nickel/cadmium battery. The principal difference between them is the use of hydrogen, absorbed in a metal hydride, for the active negative electrode material in place of cadmium. Because of its superior specific energy when compared to the Ni–Cd and its freedom from toxicity or carcinogenicity, the Ni–MH battery is superseding the Ni–Cd battery.
  The overall reaction in a Ni–MH battery is

  $$MH + NiOOH \leftrightarrow M + Ni(OH)2.$$

  When the battery is discharged, the metal hydride in the negative electrode is oxidized to form metal alloy, and nickel oxyhydroxide in the positive electrode is reduced to nickel hydroxide. During charging, the reverse reaction occurs.

At present, Ni–MH battery technology has a nominal voltage of 1.2 V and attains a specific energy of 65 Wh/kg and a specific power of 200 W/kg. A key component of the Ni–MH battery is the hydrogen storage metal alloy, which is formulated to obtain a material that is stable over a large number of cycles. There are two major types of these metal alloys being used. These are the rare-earth alloys based around lanthanum nickel, known as AB5, and alloys consisting of titanium and zirconium, known as AB2. The AB2 alloys have a higher capacity than the AB5 alloys. However, the trend is to use AB5 alloys because of better charge retention and stability characteristics.

Since the Ni–MH battery is still under development, its advantages based on present technology are summarized as follows: it has the highest specific energy (70 to 95 Wh/kg) and highest specific power (200 to 300 W/kg) of nickel-based batteries, environmental friendliness (cadmium free), a flat discharge profile (smaller voltage drop), and rapid recharge capability. However, this battery still suffers from its high initial cost. Also, it may have a memory effect and may be exothermic on charge.

The Ni–MH battery has been considered as an important near-term choice for EV and HEV applications. A number of battery manufacturers, such as GM Ovonic, GP, GS, Panasonic, SAFT, VARTA, and YUASA, have actively engaged in the development of this battery technology, especially for powering EVs and HEVs. Since 1993, Ovonic battery has installed its Ni–MH battery in the Solectric GT Force EV for testing and demonstration. A 19-kWh battery has delivered over 65 Wh kg, 134 km/h, acceleration from zero to 80 km/h in 14 sec, and a city driving range of 206 km. Toyota and Honda have used the Ni–MH battery in their HEVs — Prius and Insight, respectively.

Electro chemical process of Lithium-Polymer (Li-P) Battery.

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

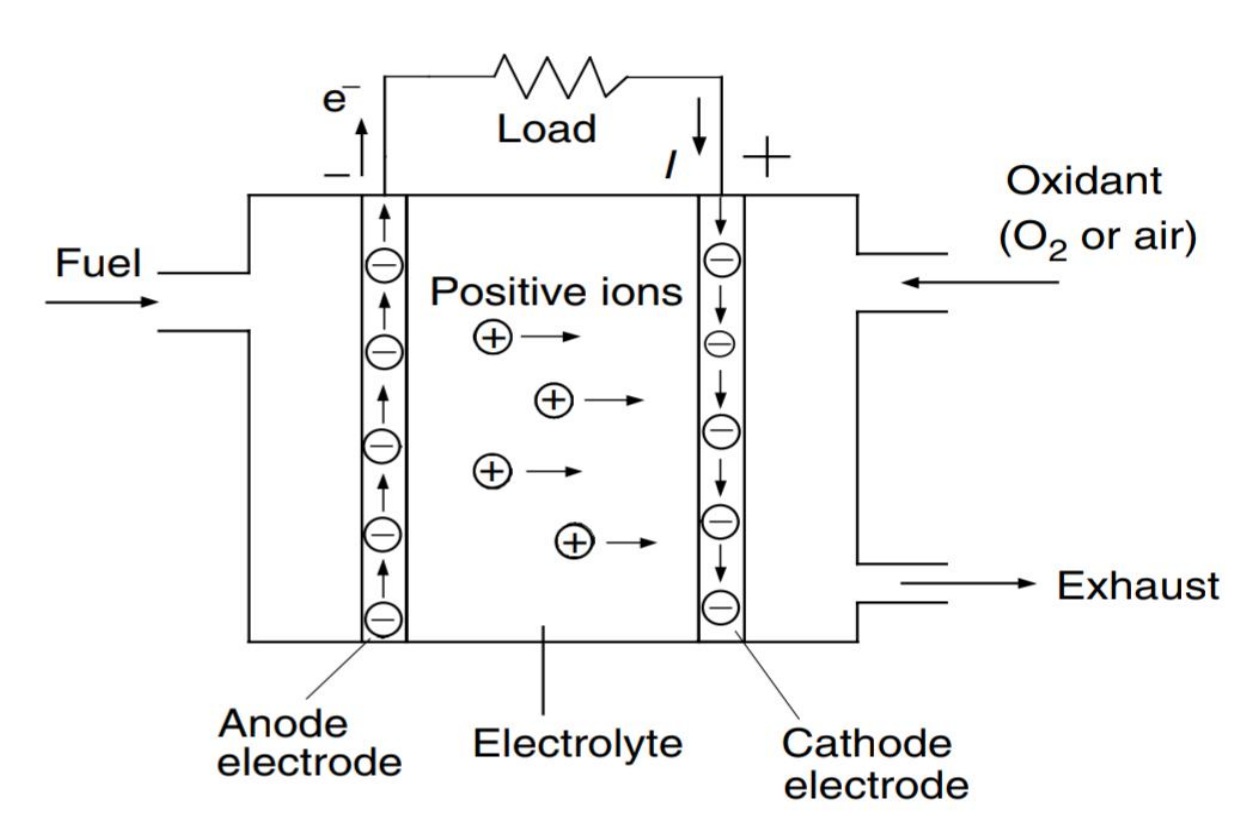
$$xLi + MyOz \leftrightarrow LixMyOz.$$

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

Fuel Cell based energy storage and its analysis

Introduction:

A fuel cell is a galvanic cell in which the chemical energy of a fuel is converted directly into electrical energy by means of electro chemical processes. The fuel and oxidizing agents are continuously and separately supplied to the two electrodes of the cell, where they undergo a reaction. An electrolyte is necessary to conduct the ions from one electrode to the other as shown in Figure.



Principle of Fuel cell

The fuel is supplied to the anode or positive electrode, where electrons are released from the fuel under catalyst. The electrons, under the potential difference between these two electrodes, flow through the external circuit to the cathode electrode or negative electrode, where, in combination with positive ions and oxygen, reaction products, or exhaust, are produced.

The chemical reaction in a fuel cell is similar to that in a chemical battery. The thermodynamic voltage of a fuel cell is closely associated with the energy released and the number of electrons transferred in the reaction.4,5 The energy released by the battery cell reaction is given by the change in Gibbs free energy, ΔG, usually expressed in per mole quantities.

Classification of Fuel Cell Technologies

- **Alkaline fuel cell (AFC)**
  This is one of the oldest designs. It has been used in the U.S. space program since the 1960s. The AFC is very susceptible to contamination, so it requires pure hydrogen and oxygen.It is also very expensive, so this type of fuel cell is unlikely to be commercialized.

- **Phosphoric-acid fuel cell (PAFC)**
  The phosphoric-acid fuel cell has potential for use in small stationary power-generation systems. It operates at a higher temperature than PEM fuel cells, so it has a longer warm-up time. This makes it unsuitable for use in cars.

- **Solid oxide fuel cell (SOFC)**
  These fuel cells are best suited for large-scale stationary power generators that could provide electricity for factories or towns. This type of fuel cell operates at very high temperatures (around 1,832 F, 1,000 C). This high temperature makes reliability a problem, but it also has an advantage: The steam produced by the fuel cell can be channeled into turbines to generate more electricity. This improves the overall efficiency of the system.

- **Molten carbonate fuel cell (MCFC)**
  These fuel cells are also best suited for large stationary power generators. They operate at 1,112 F (600 C), so they also generate steam that can be used to generate more power. They have a lower operating temperature than the SOFC, which means they don't need such exotic materials. This makes the design a little less expensive.

- **Proton exchange Membrane fuel cell (PEMFC)**
  Proton exchange Membrane (PEM) fuel cells, also known as Polymer exchange membrane fuel cells typically operate on pure hydrogen fuel. The PEM fuel cell combines the hydrogen fuel with the oxygen from the atmosphere to produce Water, heat (up to 90°C) and electricity.
- **Direct Methanol Fuel cell (DMFC)**
  The technology behind Direct Methanol Fuel Cells (DMFC) is still in the early stages of development, but it has been successfully demonstrated powering mobile phones and laptop computers, potential target end uses in future years. DMFC is similar to the PEMFC.

Proton Exchange Membrane Fuel Cells

Proton exchange Membrane fuel cells (PEMFC)

Proton exchange Membrane (PEM) fuel cells, also known as Polymer exchange membrane fuel cells typically operate on pure hydrogen fuel.

The PEM fuel cell combines the hydrogen fuel with the oxygen from the atmosphere to produce Water, heat (up to 90°C) and electricity.

PEM Fuel cells typically utilize platinum based catalysts on the Anode to split the Hydrogen into positive ions (protons) and negative electrons.

The ions pass through the membrane to the cathode to combine with oxygen from air.

PEM fuel cells use a solid polymer membrane (a thin plastic film) as the electrolyte. This polymer is permeable to protons when it is saturated with water, but it does not conduct electrons

This polymer is permeable to protons when it is saturated with water, but it does not conduct electrons.

Compared to other types of fuel cells, PEMFCs generate more power for a given volume or weight of fuel cell.

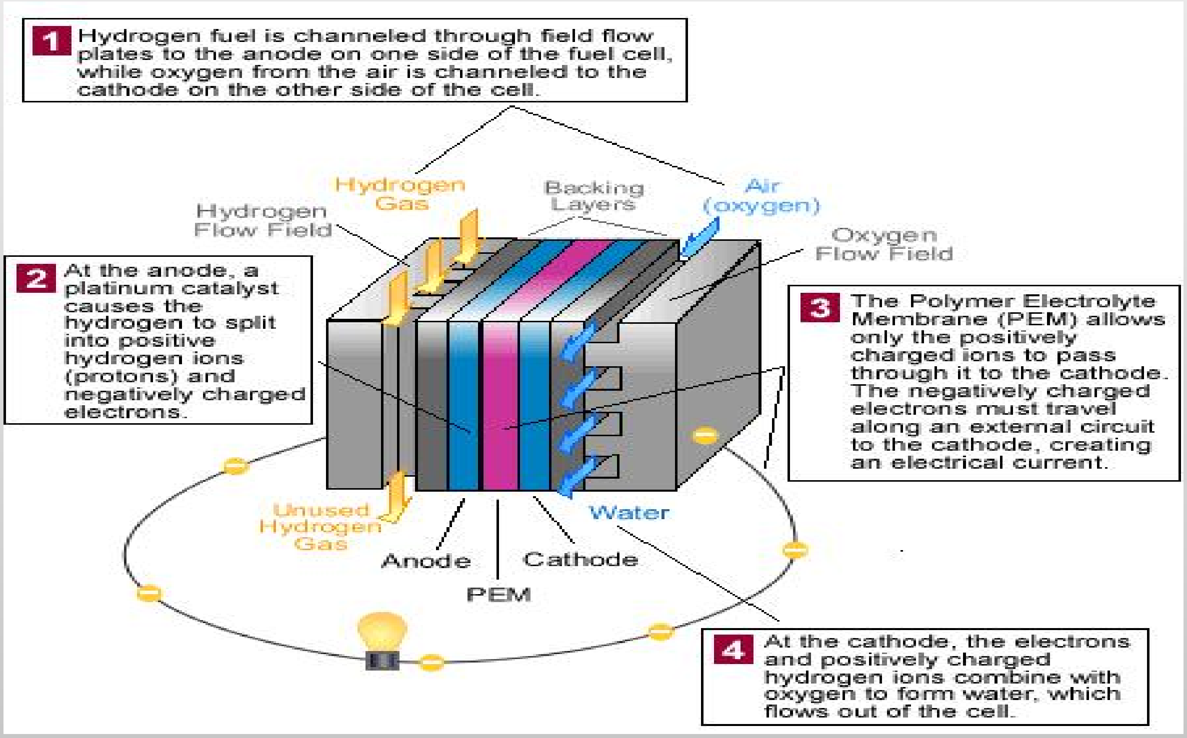
This high-power density characteristic makes them compact and lightweight. In addition, the operating temperature is less than 100°C, which allows rapid start-up.

These traits and the ability to rapidly change power output are some of the characteristics that make the PEMFC the top candidate for automotive power applications.

Other advantages result from the electrolyte being a solid material, compared to a liquid.

The sealing of the anode and cathode gases is simpler with a solid electrolyte, and therefore, less expensive to manufacture.

The solid electrolyte is also more immune to difficulties with orientation and has less problems with corrosion, compared to many of the other electrolytes, thus leading to a longer cell and stack life



Proton Exchange Membrane Fuel Cell

Alkaline Fuel Cells

Alkaline fuel cells (AFCs)

Alkaline fuel cells (AFCs) were one of the first fuel cell technologies developed, and they were the first type widely used in the U.S. space program to produce electrical energy and water on-board spacecrafts.

These fuel cells use a solution of potassium hydroxide in water as the electrolyte and can use a variety of non-precious metals as a catalyst at the anode and cathode.

High-temperature AFCs operate at temperatures between 100°C and 250°C (212°F and 482°F). However, newer AFC designs operate at lower temperatures of roughly 23°C to 70°C (74°F to 158°F)

➢ The processes that take place in the fuel cell are as follows:

Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell, while oxygen from the air is channeled to the cathode on the other side of the cell.

At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.

The positively charged hydrogen ions react with hydroxyl (OH^-) ions in the electrolyte to form water.

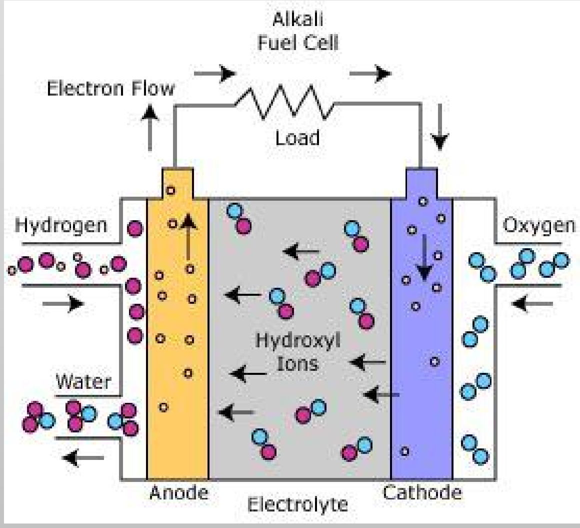
The negatively charged electrons cannot flow through the electrolyte to reach the positively charged cathode, so they must flow through an external circuit, forming an electrical current.

At the cathode, the electrons combine with oxygen and water to form the hydroxyl ions that move across the electrolyte toward the anode to continue the process.

➢ Anode Reaction: $2 H_2 + 4 OH^- \Rightarrow 4 H_2O + 4 e^-$

➢ Cathode Reaction: $O_2 + 2 H_2O + 4 e^- \Rightarrow 4 OH^-$

➢ Overall Net Reaction: $2 H_2 + O2 \Rightarrow 2 H_2O$



Alkaline Fuel Cell

Phosphoric acid fuel cell

Phosphoric acid fuel cells (PAFC) are a type of fuel cell that uses liquid phosphoric acid as an electrolyte. They were the first fuel cells to be commercialized. Developed in the mid-1960s and field-tested since the 1970s, they have improved significantly in stability, performance, and cost. Such characteristics have made the PAFC a good candidate for early stationary applications.

- **Design**

Electrolyte is highly concentrated or pure liquid phosphoric acid (H_3PO_4) saturated in a silicon carbide matrix (SiC). Operating range is about 150 to 210 °C. The electrodes are made of carbon paper coated with a finely dispersed platinum catalyst.

Electrode reactions

Anode reaction: $2H_2(g) \rightarrow 4H^+ + 4e^-$

Cathode reaction: $O_2(g) + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall cell reaction: $2 H_2 + O_2 \rightarrow 2H_2O$

- **Advantages**

At an operating range of 150 to 200 °C, the expelled water can be converted to steam for air and water heating (combined heat and power). This potentially allows efficiency increases of up to 70% PAFCs are CO_2-tolerant and even can tolerate a CO concentration of about 1.5%, which broadens the choice of fuels they can use.

If gasoline is used, the sulfur must be removed At lower temperatures phosphoric acid is a poor ionic conductor, and CO poisoning of the platinum electro-catalyst in the anode becomes severe. However, they are much less sensitive to CO than PEFCs and AFCs.

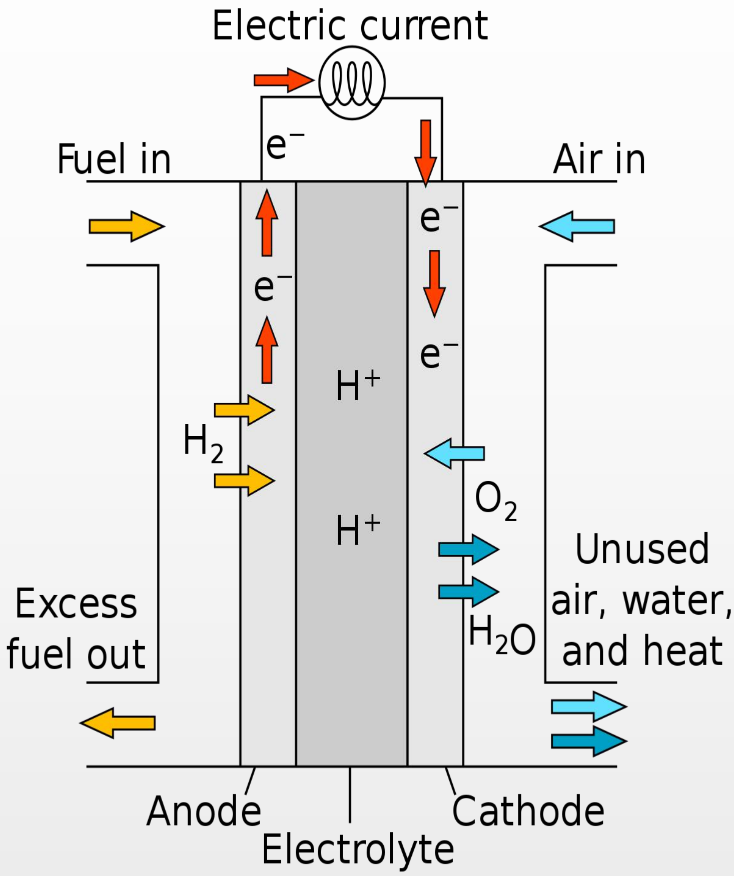
- **Disadvantages**

Disadvantages include rather low power density and aggressive electrolyte

- **Applications**

PAFC have been used for stationary power generators with output in the 100 kW to 400 kW range and are also finding application in large vehicles such as buses.

Major manufacturers of PAFC technology include Doosan Fuel Cell America Inc.(formerly Clear Edge Power & UTC Power and Fuji Electric.



phosphoric acid fuel cell

Super Capacitor based energy storage and its analysis

Basic principle of super capacitors

Super capacitor (Ultra capacitor) is a specifically designed capacitor capable of storing enormous amount of electrical charge. Super capacitors offer operational voltages that range between 1V and 3V for both aqueous and organic electrolytes. It also promises great potential for rapid charging and energy storage.

Unlike other capacitors that use the conventional dielectric, these super capacitors employ two methods for the storage of electrical energy i.e. Pseudo capacitance and double layered capacitance.

Pseudo capacitance is originally electrochemical, while double layered capacitance is electrostatic. Very high capacitances like 12000F can be achieved using this super capacitor technology.

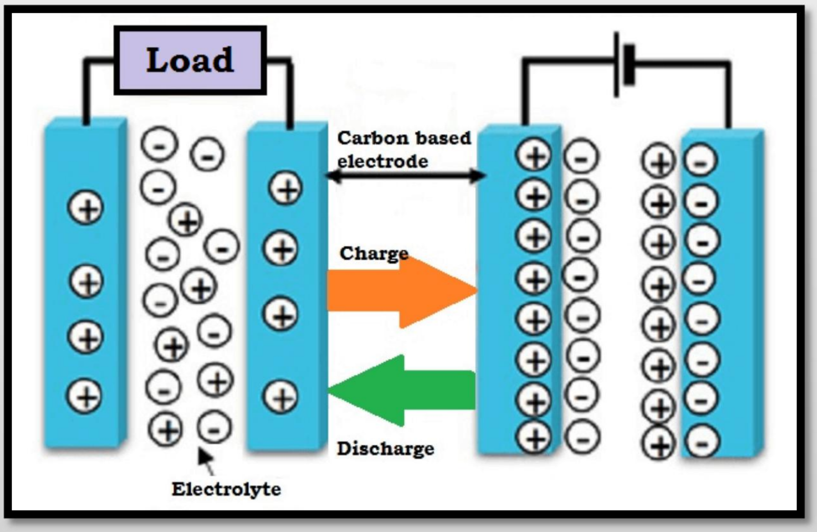
How Super capacitor (Ultra capacitor) Works

Let's first take a look at the working of a typical capacitor. Standard capacitors are made of two metallic plates or electrodes that separate a dielectric substance between them. Upon the application of voltage, electrons accumulate at one of the electrodes, thereby storing the electrical charge.

Meanwhile, the dielectric material that is wedged between the electrodes undergoes a process called "dielectric polarization" and helps to increase the capacitance.

Supercapacitor also work on the same principle except that the wedging material is an electrolytic solution rather than a dielectric substance. Upon voltage application, an "electrical double layer" will be created that aligns both negative and positive charges along the boundaries of electrodes and the electrolytic solution.

This place acts as a warehouse for storing electric charges. Activated carbon is often used to expand the boundary areas. This is because, the super capacitor's capacitance is in direct proportion to the area of "electrical double layer". This activated carbon is a known porous material and has many surface holes that help in covering a big surface area. Due to the electrolytic solution and electrodes, super capacitors share the structure of a typical battery for electricity storage. While chemical reactions take place between the electrolytic solution and the electrodes in a battery, super capacitors allow only electrons movement between electrodes. These differences result in varying properties between a battery and super capacitor.

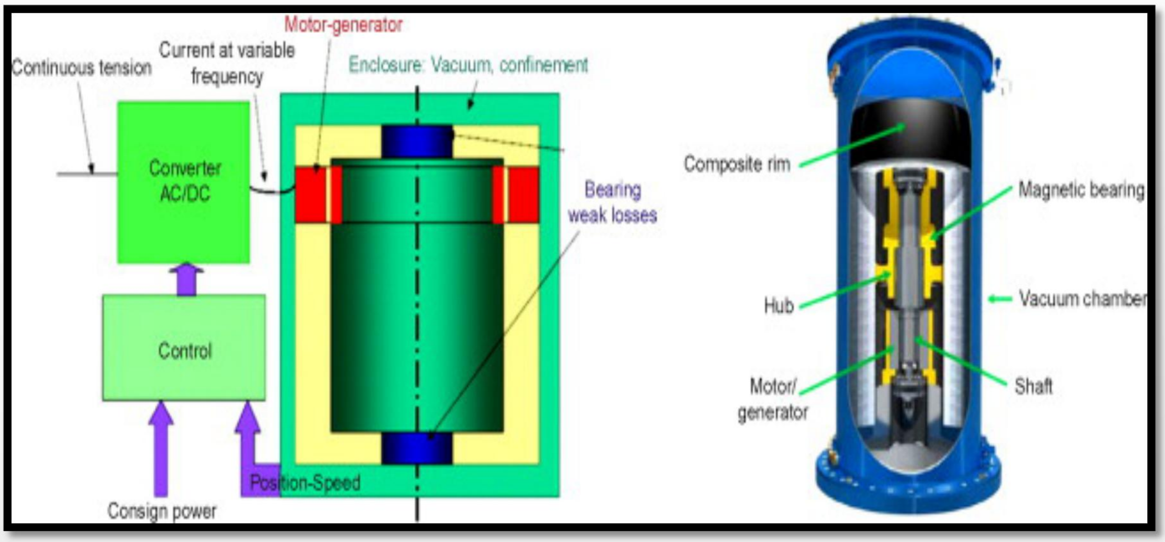


Working of Super Capacitor

Flywheel based energy storage and its analysis

Ultrahigh flywheel system

As the name indicates, kinetic energy (or rotational energy) is the key source for flywheels to store energy mechanically. The integral parts of a flywheel energy storage system are shown in Fig.They include the massive rotating cylinder component, which is supported over a stator through the magnetically levitated bearings. The flywheel is coupled with the electric generator/motor assembly for energy storage, and the entire flywheel system is placed in a low pressure (or vacuum) atmosphere to reduce shear disturbances/frictional losses due to wind or external forces.



Ultra High Flywheel

The flywheel system operates on the principle of kinetic energy for storing and releasing energy depending on load demand. During the storage period, the flywheel system rotates at very high speed by means of electric motor activation. During the discharging cycle, the stored kinetic energy in the flywheel is utilized for regenerating the motor to function as an electric generator. By providing proper power controls and power converters, the required energy demand can be effectively met. Because the kinetic energy stored in the flywheel system is directly proportional to its mass and the square of the velocity (rotating speed), maximum energy storage density depends on the tensile strength of the flywheel material. Furthermore, the shape and the inertial effects of the rotating component also decide the quantity of energy being stored by the flywheel.

Hybridization of different energy storage devices

Hybridization of Energy Storages

The hybridization of energy storage is to combine two or more energy storages together so that the advantages of each one can be brought out and the disadvantages can be compensated by others.

For instance, the hybridization of a chemical battery with an ultracapacitor can overcome such problems as low specific power of electrochemical batteries and low specific energy of ultra-capacitors, therefore achieving high specific energy and high specific power

The hybridized energy storage consists of two basic energy storages: one with high specific energy and the other with high specific power.

In high power demand operations, such as acceleration and hill climbing, both basic energy storages deliver their power to the load as. On the other hand, in low power demand operation, such as constant speed cruising operations, the high specific energy storage will deliver its power to the load and charge the high specific power storage to recover its charge lost during high power demand operation.

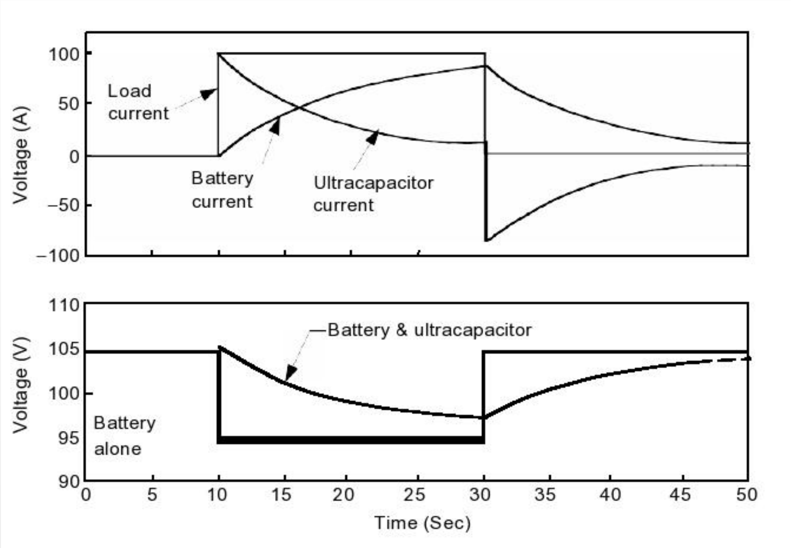
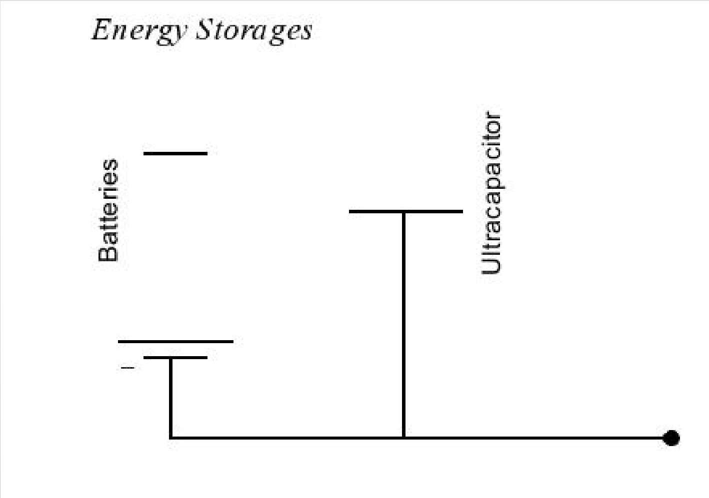


FIG. Variation of battery and ultra-capacitor currents and voltages with a step current output change

In regenerative braking operations, the peak power will be absorbed by the high specific power storage, and only a limited part is absorbed by the high specific energy storage. In this way, the whole system would be much smaller in weight and size than if any one of them alone was the energy storage.

Based on the available technologies of various energy storages, there are several viable hybridization schemes for EVs and HEVs, typically, battery and battery hybrids, and battery and ultra-capacitor hybrids.



The latter is more natural since the ultra-capacitor can offer much higher power than batteries, and it collaborates with various batteries to form the battery and ultra-capacitor hybrids.

In this configuration, the ultra-capacitors simply act as a current filter, which can significantly level the peak current of the batteries and reduce the battery voltage drop. The major disadvantages of this configuration are that the power flow cannot be actively controlled and the ultra-capacitor energy cannot be fully used.

The batteries and the ultra-capacitors to have a different voltage, the power flow between them can be actively controlled, and the energy in the ultra-capacitors can be fully used. In the long term, an ultrahigh-speed flywheel would replace the batteries in hybrid energy storage to obtain a high efficiency, compact, and long-life storage system for EVs and HEVs.

UNIT-3

SIZING THE DRIVE SYSTEM

Matching of electric machine and internal combustion engine (ICE)

- One of the most common matching elements used in hybrid electric passenger vehicles is the epicyclic, or planetary, gear set. Continuously variable transmissions of the compression belt and toroidal variator variety are gaining popularity in compact vehicles and passenger vans because of seamless transitions in ratio. For larger CVTs the issues of torque rating and efficiency at high ratio continue to be developmental areas.

  Figure 4.1 shows the epicyclic gear in schematic form. This is a three-port mechanical component used as a speed summing device. Most designs rely on a dual input and single output where one input source is the ICE and the second input comes from an electric M/G. Epicyclic gear ports may be defined as input or output according to the convection illustrated in Table 4.1. The epicyclic basic ratio, $k = R_{ring}/ R_{sun}$ where R_x is the radius of ring and sun gears (can also be defined in terms of number of gear teeth).

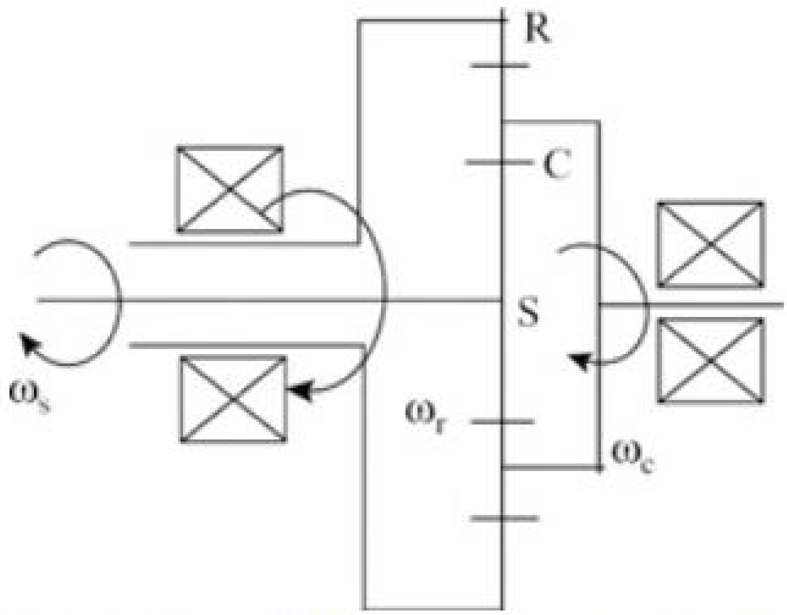
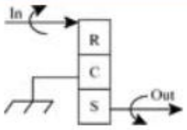
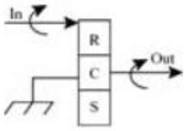
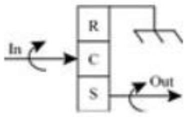


Figure 4.1: Schematic of epicyclic gear set

Table 4.1: Epicyclic gear input output relationships

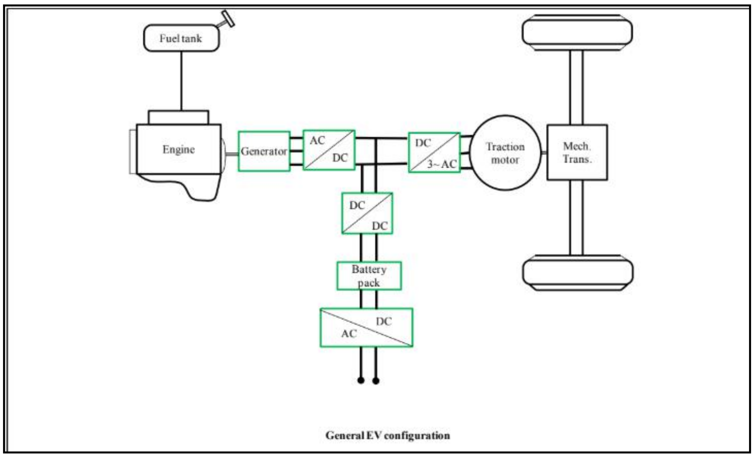
Configuration	Direction of speed	Grounded port	Input port	Output port
	Reversed	Carrier $N_c = 0$	Ring N_r	Sun $N_s = ?\ kN_r$
	Normal	Sun $N_s = 0$	Ring N_r	Carrier $N_c = (k/(k+1))\ N_r$
	Normal	Ring $N_r = 0$	Carrier N_c	Sun N

Sizing of propulsion motor

An EM is at the core of HEV drivetrains. The electric energy path of HEV consists of an energy storage unit (such as batteries, super capacitors or fuel cells), a power processing
unit (such as DC-AC converters) and an EM. In Figure 1 a schematic of hybrid propulsion system is shown.

- **Most EMs used in HEV or EV drivetrains have speed limit of 12000 rpm due to following reasons:**
  - At very high rpm, the centrifugal force acting on the rotor increases and it is possible that the rotor might fail mechanically.
  - The control algorithms of the EM involve determination of rotor position and this becomes very difficult at high rotor rpm.

- **The performance of EM is measured by following quantities:**
  - Torque and Power Capability
  - ii. Constant Power Speed Ratio (CPSR)



General Configuration

Sizing of power electronics

In Figure 4 a schematic for the HEV drivetrain consisting of on-board energy storage system, power processing unit and the EM is shown. The power electronics is an electrical element in much the same manner that a gearbox processes mechanical power to match the ICE to the road requirements.

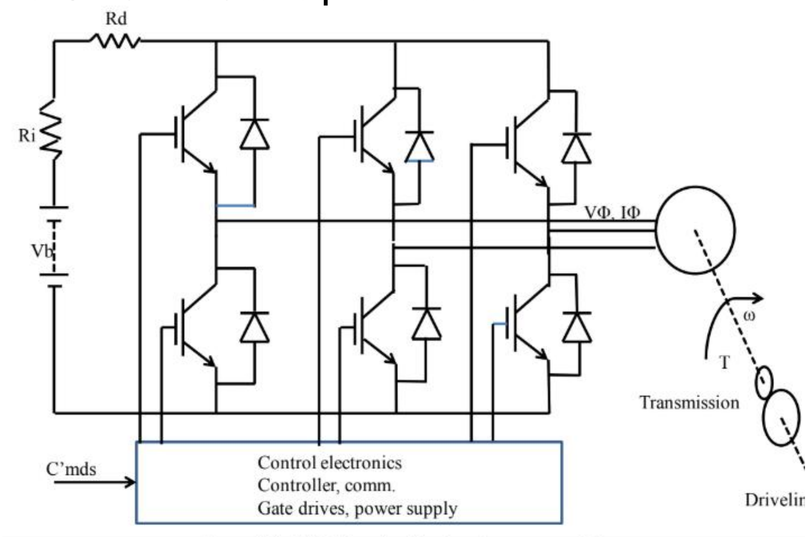


Figure 4: The HEV drivetrain with on board energy storage [2]

HEV Drivetrain On Board Enegry System

The power processing capability of power inverters is directly related to the dc input voltage available. Higher voltage means more throughput power for the same gauge wiring.

The throughput power versus the voltage is shown in Figure 5. From Figure 5a it can be seen that as automotive voltages move towards 42V, the sustainable power level will approach 10kW. For hybrid propulsion the Figure 5a shows that

voltages in excess of 150V are advisable. With recent advances in power electronic switches it is possible to move to voltage beyond 300V.
The figure 5b shows that most of the hybrid propulsion systems such as Toyota Hybrid System, Honda IMA, etc. are clustered along the 100A trend line. Virtually all power electronics inverters for hybrid propulsion use IGBT device technology. Power semiconductor device range in voltage withstanding capability from 2kV to 6.5kV and current magnitudes from 3kA to 4.5kA.
Thyristors have the highest kVA rating but are generally slow switching. The gate turns off thyristor (GTO) is capable of handling 3kA at 4.5kV but can switch at only 700Hz. The IGBTs have made enormous progress in both the voltage and current ratings, with some IGBTs being capable of handling 6.5kV and 3.5kA and have switching frequency up to 100kHz.

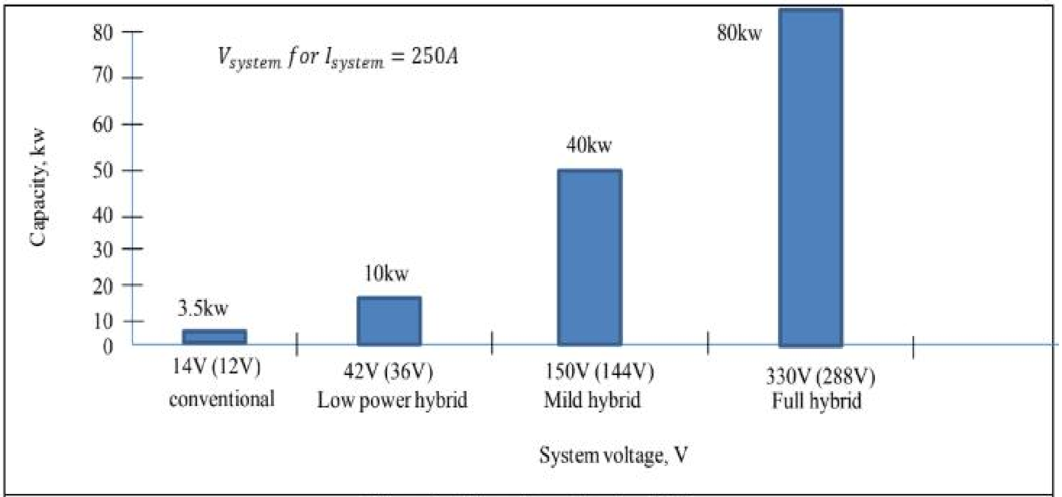


Figure 5a: Automotive voltage trend [2]

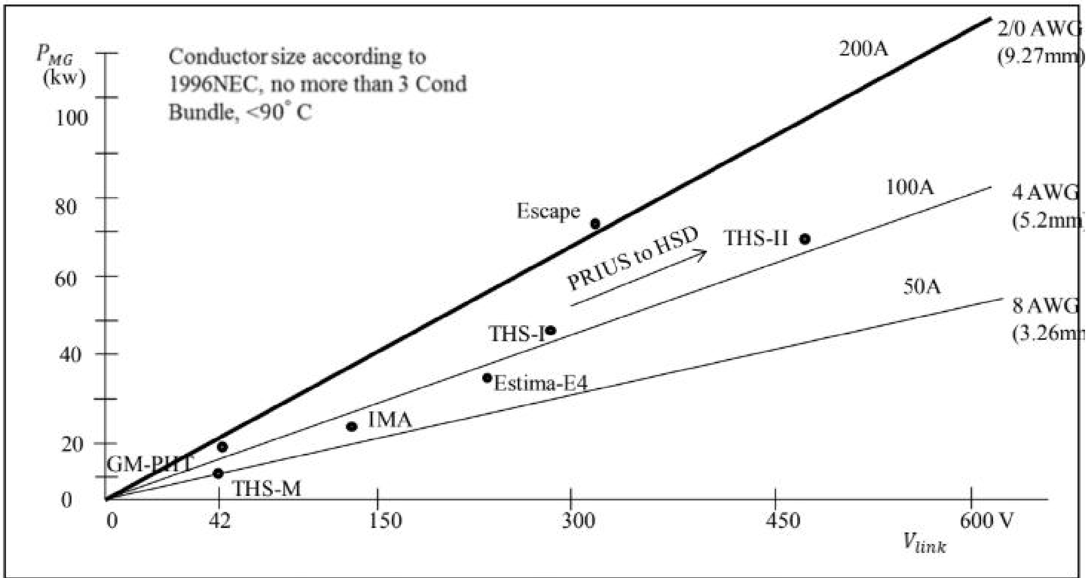


Figure 5b: Voltage levels of different hybrid drivetrains [2]

Automotive communications networks used in EV and HEV vehicle

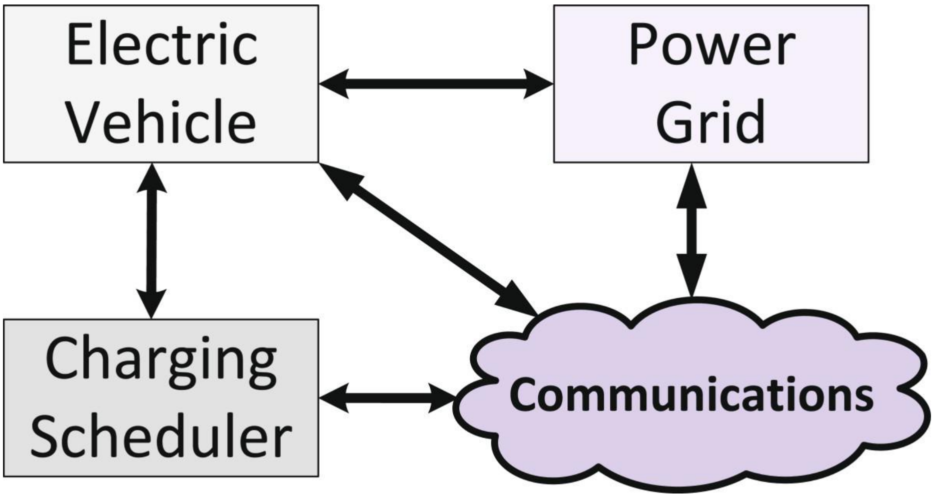
As the dependence on a single energy source (crude oil) exposes economies to unstable global oil market and increases environmental concerns, there has been a growing interest to push electric vehicles into mainstream acceptance. The motivation for the electrification of transportation is multifaceted; electricity can be generated through diverse and domestic resources, electricity prices have been relatively stable in the last two decades, and electric miles are cheaper and cleaner. Therefore, internet of electric vehicles are expected to achieve a sizable market portion in the next decade. In fact, the study in estimates that there will be around 50 million grid-enabled vehicles by year 2040.

However, as the power grid is becoming more congested due to the introduction of EVs, managing and controlling of corresponding demand should be carefully aligned with the available resources. Even though, the long term solution involves the upgrade of the power grid components, by considering the potential cost of such investments, the practical solution for the near term would be to develop intelligent control and scheduling techniques to aid the power grid operations. The realization of such frameworks requires appropriate communication architectures that will enable reliable interaction between the grid and the EV drivers to optimally control power flow under varying network conditions.

The transmission network ties the bulk power generation with the end users via high voltage lines. The US national grid includes three distinct geographic interconnections, namely the Eastern Interconnection, the Western Interconnection, and the Electric Reliability Council of Texas. The transmission network is composed of 170,000 miles of transmission lines rated at 200 (kV) and above, delivering the power generated at 5,000 (approximately) power plants. Over the last two decades, the transmission network acts as an open highway which connects wholesale electricity markets to with end users. The primary goal of the network operators, on the other hand, is to make sure that transmission lines operate efficiently and reliably as it delivers the minimum cost generation to end users.

The introduction of bidirectional chargers enables electric vehicles to transfer energy back to the grid (V2G) or to other electric vehicles (V2V). The utilization of such ancillary services can aid the transmission operations, mainly by reducing the congestion during peak hours. For example, group of vehicles can sell back part of their stored energy to other EVs who are in urgent need. This way, energy trading via V2V will eliminate the need to draw power from bulk power plants and hence the associated power losses in transmission will be minimized. For instance, studies in present mathematical framework to model the interaction of energy trading in a V2V scenario, where the groups of EVs determine the amount of energy to exchange and negotiate on unit price.

Moreover, EVs can transport their stored energy from one location to another which can support the grid via V2G applications. For example, providesa transmission network based on the capability Internet of vehicles to transfer energy to the regions of high energy consumption. This way, the required upgrades will be deferred and occur gradually over time.



Network communication flow chart

Different types of supporting subsystems used in EV and HEV vehicles

The rapid growth of the electric vehicle market has stimulated the attention of power electronics and electric machine experts in order to find increasingly efficient solutions to the demands of this application.

The constraints of space, weight, reliability, performance, and autonomy for the power train of the electric vehicle (EV) have increased the attention of scientific research in order to find more and more appropriate technological solutions.

In recent years, hybrid and electric vehicles have always gained more market share. These cars are equipped with an *energy storage system* (*ESS*, typically batteries), also integrating an *ICE* in the case of hybrid vehicle.

Despite the presence of an electric motor/generator and a battery, it is not possible to define a hybrid car a zero-emission vehicle. Therefore, before addressing the main issues of our topic, it is important to better define the different topologies of hybrid/electric cars, as briefly

➢ **Zero-emission vehicles (ZEVs)**

Full electric vehicles, otherwise known as battery electric vehicles *(*BEV*) or* pure electric vehicles (*PEV*), are wholly driven by an electric motor, powered by a battery that can be plugged to the grid. There is no combustion engine. Indeed, several subsystems can be identified and each of these performs a specific mission also interacting with one or more other subsystems. The main macroblocks identified are:

a. **The energy storage system**: Usually the battery pack with its management system (*battery management system* also called *BMS*), which is designed to accumulate and supply energy.

b. **DC/AC converter***:* It is the power interface between the storage and the electric motor. It not only has the task of adapting the power supply but it also play important control functions, as will be fully described later.

c. **Motor***:* The electric motor, which can also be operated as a generator in case of the adoption of the regenerative braking, has the task of carrying out the conversion of electric energy coming from the *ESS* into mechanical energy to be supplied to the mechanical transmission to allow the car motion.

d. **Charging interface***:* The charging interface is essential for a ZEV, as it must allow the batteries to be recharged onboard. The charging interface includes different kinds, depending on the type/types of recharge that it wants to adopt (even more types on the same vehicle).

e. **Control layer**: The supervisor and data acquisition system is dedicated to processing driving information and transforming it into references for the aforementioned power subsystems.

f. **Auxiliary load***:* The auxiliary loads, which will not be analyzed in this chapter, represent all the utilities onboard that need a power supply. Typically, the power of these loads occurs at a much lower voltage of the main voltage of the DC-bus, for example, 12 V, and must be galvanically insulated, for safety reasons, since this last. The power supply of the auxiliary load, therefore, is derived from the DC-bus through a DC/DC converter with electronic transformer (e.g., *flying bridge converter* or *isolated switch mode power supply*) which ensures the request insulation condition.

g. **Mechanical transmission***:* The mechanical transmission of an electric vehicle takes care of converting the energy coming from the electric motor into mechanical energy of movement, distributing it directly to the wheels of the car. This element has been borrowed from traditional vehicles and therefore has poor interest in carrying out its analysis here.