Energy Storage Systems for Totally Electric Hybrid Vehicles

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Abstract— **This paper presents different types of energy sources and storage systems for total electric hybrid vehicles. The main source of energy that can be used in the construction of electric vehicles is fuel cell. As a dedicated storage system for electric vehicles is electric battery and more recently has been developed a new system that uses ultracapacitors. By combining fuel cells with existing storage systems result a hybrid system that put together these properties to obtain high performance, in the vehicles which will be used, in terms of autonomy, maximum speed and comfort.**

Index Terms—**battery, electric hybrid vehicle, energy storage system, fuel cell, ultracapacitor.**

I. INTRODUCTION

Currently, the Fuel-Cell Vehicle and the Battery Electric Vehicle are the only potential zero emissions vehicle replacements of the internal combustion engine. Scientists are developing many different types of fuel cell employing different fuels and electrolytes. One of the most promising is the lightweight, relatively easy to build and small Polymer Electrolyte Membrane Fuel Cell (PEMFC), first used by NASA in the 1960's as part of the Gemini space program [1]. Fuel cell power generation systems are expected to increase in utilization in different applications such as stationary loads, automotive applications, and interfaces with electric utilities due to the numerous advantages over conventional generation systems. One characteristic of fuel cells comparing whit internal combustion engine is that highest efficiency is attained at a small fraction of maximum output power. The internal combustion engine has maximum efficiency on much larger span. The main weak point of fuel cell is its slow dynamics. In reality, the dynamics of fuel cell is limited by the hydrogen and oxygen delivery system, which contains pumps and valves, and in some cases a hydrogen reforming process [2].

A reliable (rechargeable) battery of high energy and power density is needed to obtain performance with an electric vehicle that uses batteries for propulsion. Li-ion batteries are most likely to be commercialized for electric vehicle applications. Because lithium is the metal with the highest negative potential and lowest atomic weight, batteries using lithium have the greatest potential for attaining the technological breakthrough that will provide electrical vehicles with the greatest performance characteristics in terms of acceleration and range. Unfortunately, lithium metal, on its own, is highly reactive with air and with most liquid electrolytes. To avoid the problems associated with metal lithium, lithium intercalated graphitic carbons are used and show good potential for high performance, while maintaining cell safety [3].

Recently, a very promising technology has been introduced with the potential to improve energy storage in automotive applications: double-layer capacitors. These devices, also known as ultracapacitors or supercapacitors, represent a new generation of electrochemical components with very high capacitance for energy storage. Ultracapacitor packs are now offered as a standard energy storage option on electric drive systems and are a viable component for production-intent designs. They offer excellent performance, wide temperature range, long life, and flexible management. In vehicles up to 25% of the total energy used is uselessly converted to heat during braking. This effect is even more critical in urban traffic. Therefore a solution is to introduce an energy storage system that allows storage of the braking energy which can then be applied to acceleration. Regenerative braking is thus absolutely imperative to extend the range of EVs. However this method of energy saving can also be usefully applied to vehicles with internal combustion engines.

As you can see, all equipments, which can form the total electric hybrid systems, have advantages and disadvantages. Combining advantages for obtaining high performance is very possible and viable.

II. MAIN COMPONENTS

A. *Fuel cells*

Fuel cells are electrochemical devices that convert chemical energy in fuels into electrical energy directly. Because the intermediate steps of producing heat and mechanical work typical of most conventional power generation methods are avoided, fuel cells are not limited by thermodynamic limitations of heat engines such as the Carnot efficiency. In addition, because combustion is avoided, fuel cells produce power with minimal pollutant. However, unlike batteries the reductant and oxidant in fuel cells must be continuously replenished to allow continuous operation. Fuel cells bear significant similarity to electrolyzers. Some fuel cells operate in reverse as electrolyzers, yielding a reversible fuel cell that can be used for energy storage. This type of fuel cells is named reversible fuel cells. Well known types of this are vanadium redox-flow batteries.

The different fuel cell types are usually distinguished by the electrolyte that is used, though there are always other important differences as well.

TABLE I. DIFFERENTS TIPES OF FUEL CELL

Type	Mobile ion	Operating temperature	Applications and notes
Alkaline (AFC)	OH^-	50-200˚C	Space vehicles
Phosphoric Acid (PAFC)	H^+	≈220˚C	Combined heat and power systems of 200kW
Molted carbonate (MCFC)	CO_3^{2-}	≈650˚C	Medium to large scale combined and power systems
Direct methanol (DMFC)	H^+	20-90˚C	Portable electronics of low power, running long times
Proton exchange membrane (PEMFC)	H^+	30-100˚C	Vehicles and mobile applications
Solid oxide (SOFC)	O^{2-}	500-1000˚C	All sizes of combined heat and power systems, 2kW 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 1.

The proton exchange membrane fuel cell (PEMFC) was first developed by General Electric in the United States in the 1960s for use by NASA on their first manned space vehicles. The electrolyte is an ion conduction polymer. Onto each side is bonded a catalysed porous electrode. The mobile ion in the polymers used is an H^+ ion or proton, so the basic operation of the cell is essentially the same as for the acid electrolyte fuel cell. The polymer electrolytes work at low temperatures (60^o to 80^oC), which has the advantage that a PEMFC can start quickly. The reactions that take place at the anode and cathode electrode are:

$$\text{Anode:} \quad H_2 \rightarrow 2H^+ + 2e^- \tag{1}$$

$$\text{Cathode:} \quad O_2 + 4e^- + 4H^+ \rightarrow 2H_2O \tag{2}$$

Typical cell components are show in the figure below:

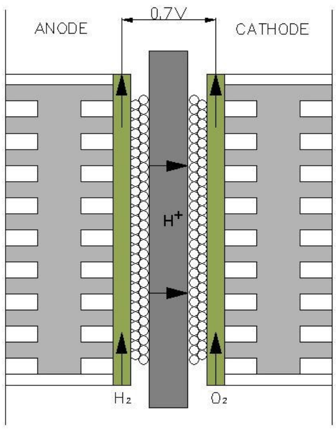

Fig. 1 Schematic PEMFC

Electrons, which appear on the anode side, cannot cross the membrane and are used in the external circuit before returning to the cathode. Proton flow is directly linked to the current density:

$$J_H = i/F \tag{3}$$

where F is the Faraday's constant.

The value of the output voltage of the cell is given by ΔG, where ΔG is Gibb's free energy:

$$V_{out} = -\Delta G/2F = 1,23V \tag{4}$$

However, when a fuel cell is made and put to use, it is found that the voltage is less than this, often considerably less. The main causes of voltage drop are the activation losses which are caused by the slowness of the reactions taking place on the surface of the electrodes, fuel crossover and internal currents which means that exist an energy loss as a result of fuel passing through electrolyte and from electron conduction through electrolyte, ohmic losses caused by straightforward resistance to the flow of electrons through the material of electrodes and the various interconnections, as well as the resistance to the flow of ions through electrolyte and finally concentration losses as a result at change in concentration of the reactants at the surface of the electrodes as the fuel is used [1].

B. Li-Ion Batteries

In 1991, the first lithium secondary battery of high quality and revolutionary concept was put on the market by Sony. In the commercial battery, called the "lithium ion battery", lithium ions swing between the anode and the cathode through an organic liquid electrolyte dissolving an anorganic lithium salt. The principal concept is based on the intercalation reaction and is rather different from conventional batteries which are based on chemical reactions.

An electrochemical cell interfaces the external world through two metallic posts: one contacts a negative electrode (the anode) and the other a positive electrode (the cathode) as illustrated schematically in figure 2. During cell discharge, electrons pass from the anode to the cathode through an external load of resistance and ions flow inside the cell to convert chemical energy into electrical energy [4].

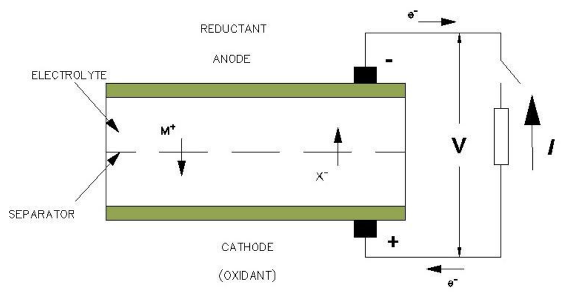

Fig. 2 Schematic Li-Ion Battery

The electronic current *I* delivered by the cell to the external circuit is matched by the ionic current within the cell. Any leakage of electrons from anode to cathode within the cell reduces the current *I* delivered by the cell. During cell charge, electric current is forced in the opposite direction by an externally applied voltage to convert electrical energy back into chemical energy. The ionic current within an electrochemical cell is carried between the electrodes by an electrolyte, which is ideally an electronic insulator and a good conductor of the working ion of the cell. The output power of the Li-Ion battery is:

$$P = IV \tag{5}$$

The voltage across the positive and the negative electrods is:

$$V = V_0 - IR_b \tag{6}$$

As we can see the external load voltage V is reduced with factor IR_b due to the internal resistance R_b of the battery.

Manufacturers of lithium-ion cells have very strict guidelines in charge procedures and the pack should be charged as per the manufacturers "typical" charge technique.

The rate of charge or discharge is often expressed in relation to the capacity of the battery. This rate is known as the C-Rate. The C-Rate equates to a charge or discharge current and is defined as:

$$I_{cd}=MxC_n \tag{7}$$

where I_{cd} is charge-discharge current, M is a multiple or fraction of C and C is numerical value of rated capacity and n is time in hours at C is declared. A battery discharging at a C-rate of 1 will deliver its nominal rated capacity in one hour. For example, if the rated capacity is 1000mAhr, a discharge rate of 1C corresponds to a discharge current of 1000mA. A rate of C/10 corresponds to a discharge current of 100mA. During a Li-ion battery's discharge, lithium ions are released from the anode and travel through an organic electrolyte toward the cathode. Organic electrolytes are stable against the reduction by lithium. When the lithium ions reach the cathode, they are quickly incorporated into the cathode material. This process is easily reversible. Because of the quick reversibility of the lithium ions, lithium-ion batteries can charge and discharge faster than Pb-acid and NiMH batteries. In addition, Li-ion batteries produce the same amount of energy as NiMH cells, but they are typically 40% smaller and weigh half as much.

C. Supercapacitors or ultracapacitors

In HEV design, the peak power capacity of the energy storage is more important than its energy capacity, and usually constrains its size reduction. Based on present battery technology, battery design has to carry out the trade-off among the specific energy and specific power and cycle life. The difficulty in simultaneously obtaining high values of specific energy, specific power, and cycle life has led to some suggestions that the energy storage system of EV and HEV should be a hybridization of an energy source and a power source. The energy source, mainly batteries and fuel cells, has high specific energy whereas the power source has high specific power. The power sources can be recharged from the energy source during less demanding driving or regenerative braking. The power source that has received wide attention is the ultracapacitor.

The ultracapacitor is characterized by much higher specific power, but much lower specific energy compared to the chemical batteries. Its specific energy is in the range of a few watt-hours per kilogram. However, its specific power can reach up to 3 kW/kg, much higher than any type of battery. Due to their low specific energy density and the dependence of voltage on the SOC, it is difficult to use ultracapacitors alone as energy storage for electric vehicles. Double-layer capacitor technology is the major approach to achieving the ultracapacitor concept [5]. Basically, an ultracapacitor is an electrochemical double layer capacitor consisting of two electrodes, which are immersed into an electrolyte as in figure 3. The electrode in most ultracapacitors is carbon combined with an electrolyte. When the electrodes are being electrically charged, the ions of the electrolyte move under the influence of the electric field towards the electrodes of opposite charge. In the charged state, a fraction of the anions and cations are located adjacent to the electrode such that they balance the excess charge in the activated carbon. Thus, across the phase boundary between carbon and electrolyte there are two layers of excess charge of opposed polarity. This is called an electrochemical double layer. Charge and discharge performs upon movement of ions within the electrolyte. The more or less randomly distributed ions move under the influence of the electric field toward the electrodes of opposite charge. Consequently, there are some fundamental property differences between UltraCap and battery technologies, which result in long shelf life, extended useful life, high cycle life and a maintenance-free product [6].

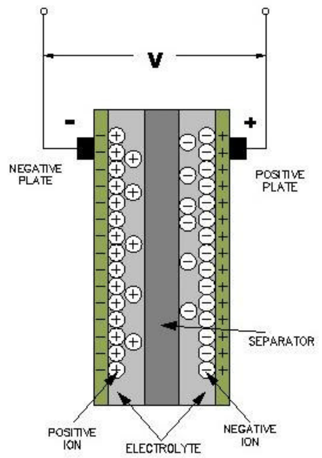

Fig. 3 Schematic ultracapacitor

An electrical double layer works as an insulator only below the decomposing voltage. The stored energy, E_{cap}, is expressed as:

$$E_{cap} =1/2\ CV^2 \tag{8}$$

where C is the capacitance in Farads and V is the usable voltage in volts. This equation indicates that the higher rated voltage V is desirable for larger energy density capacitors. Up to now, capacitors rated voltage with an aqueous electrolyte has been about 0.9V per cell, and 2.3 to 3.3 V for each cell with a nonaqueous electrolyte.

The potential uses for ultracapacitors in the automotive industry are increasing rapidly because transportation markets demand not only raw performance, but long operating life, wide temperature ranges, and low cost. This is especially true in systems requiring high power. Ultracapacitors offer a long cycle life and excellent cold temperature performance, and the basic materials used in their construction pose no significant barriers to affordable cost in quantities typical of the automotive market.

III. HYBRID SOLUTIONS

Hybrid models have emerged as a necessity of development of electric vehicles. Development of hybrid vehicles means to obtain performance similar or greater than those with internal combustion engine and also small costs of production, sales and operating. Nowadays there are electric vehicles on the market that have comparable performance to those with internal combustion engines but the price is high. In addition, as long as there will be fossil fuel, electric vehicles will not be the first option in choice of a vehicle unless have high performance, are reliable and a cost price of at least similar to that of vehicles with internal combustion engines. Hybrid applications use two different power sources to solve two different power requirements. One which acts as the primary power source, is sized for the continuous load requirement. Second, which acts as the secondary power source, is sized for the peak load requirement. The main configurations for totally electric hybrid vehicles are: fuel cell – batery, baterry – ultracapacitor, fuel cell – ultracapacitor, fuel cell – battery - ultracapacitor.

A. Battery – ultracapacitor

Combining a battery and an ultracapacitor to operate in parallel is an attractive energy storage system with many advantages. Such a hybrid system uses both the high power density of ultracapacitor as well as the high energy density of the battery [8]. For study, an electrical equivalent model system of such system will be presented, which can be used to evaluate its voltage behavior. The model is depicted in Fig. 4.

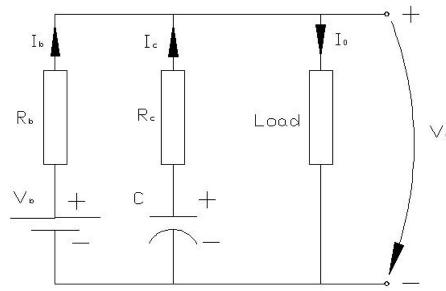

Fig. 4 Equivalent circuit model of a battery – ultracapacitor system

The equivalent circuit shows an equivalent series resistance R_c and a capacitor C as a model of ultracapacitor, whereas the Li-Ion battery can be modeled simply by using a resistance R_b and a battery. The values of R_c and C depend on the frequency due to the porous nature of the electrodes of the ultracapacitor. When the pulse-width T is varied, the discharge rate of the ultracapacitor can be varied and can be shown to be equal to a frequency *1/T*. The fallowing equations can be written for I_0 and V_0 from the equivalent circuit model:

$$I_0 = I_c + I_b \tag{9}$$

$$V_0 = V_b - I_b R_b = \left[V_b - \frac{1}{C}\int_0^T I_c dt \right] - I_c R_c \tag{10}$$

Here, I_0 and V_0 are the output current and voltage delivered to the load. From the above two equations it is possible to achieve a voltage drop $\Delta V = V_b - V_0$ due to a pulse current of I_0. This voltage drop can be finally expressed as:

$$\Delta V = \frac{I_0 R_b R_c}{R_b + R_c + \frac{T}{C}} + \frac{I_0 R_b \frac{T}{C}}{R_b + R_c + \frac{T}{C}} \tag{11}$$

The currents delivered by the battery (Ib) and capacitor (Ic) can also be derived and their ratio can be expressed as:

$$\frac{I_c}{I_b} = \frac{R_b}{R_c + \frac{T}{C}} \tag{12}$$

It can be seen that for a long pulse, I_c can be limited by the value of C. Furthermore, it can be concluded that during the pulsed discharge, about 40-50% of the total current is delivered by C. During peak power demand, ultracapacitor delivers energy to assist the battery whereas, during low power demand, ultracapacitor receive energy from the battery [8] if is necessary because usually the ultracapacitor receive energy via regenerative breaking in deceleration period. In this configuration, the ultracapacitor role is to reduce the battery voltage drop at high power demand and to leverage the energy transfer through regenerative breaking utilization. Typical advantages are longer range for quiet operation, better acceleration, higher fuel mileage, and lower maintenance.

B. Fuel cell – battery

This hybrid system has as primary source of energy the PEMFC and as secondary source Li-Ion batteries. The battery provides power during start-up and acceleration, and the fuel cell supplies the steady state load. When the total power requirements of the vehicle are low, then the surplus electrical energy is stored in rechargeable battery. When the power requirements exceed those that can be provided by the fuel cell, then energy is taken from the battery. This system is not very efficient if the power requirement is constant. To determine the battery size, three conditions must be satisfied: output power, output voltage level, energy capacity. The battery size is decided by the number of series and parallel cells, and the most important part of sizing is selecting the optimum number of cells in the battery. Here, the number of cells in series determines the voltage level, and the number of cells in series and parallel determines the battery energy capacity (Ah). The output power of a battery in a fuel cell – battery system should be optimized to satisfy the maximum required power while boosting the fuel cell. In this case the output power is:

$$P_{bat} = \frac{P_{mot}}{\eta_{mot}} - P_{PEMFC} \tag{13}$$

where P_{bat} is battery power, P_{mot} is maximum motor power required, η_{mot} is motor efficiency and P_{PEMFC} is the fuel cell maximum power. Output voltage level is determined by the main bus voltage of the vehicle. If the bus voltage is very high then we can use a boost converter to adapt the battery voltage. In large part the battery voltage is determined by the number of batteries in series. Energy capacity is very important to be determined because we must be sure that designed battery can deliver enough power in time to the motor. The energy capacity can be express as:

$$\frac{1}{2}QV_{0c} = \int (V_{0c} x I) dt = \int P\, dt \qquad (14)$$

where Q is battery capacity, V_{0c} is open circuit voltage and I is battery current.

As we can see from the above, in a fuel cell – battery system where the fuel cell is the primary source, the battery should be dimensioned only for a part of the maximum power required to traction motor. This implies significant savings in construction of fuel cell and a high reliability because the mechanical, electrical and chemical stress to which are subjected is reduced. Therefore in this configuration is preferable to use PEMFC in parallel with Li-Ion batteries which have a high specific energy and a small volume.

C. Fuel cell – ultracapacitor

Necessity of this system was felt when the vehicle manufacturers was able to produce electric vehicles with fuel cells as primary energy sources. Fuel cells can exhibit the highest energy density of all electrochemical energy storage and conversion devices; therefore the fuel is well suited to provide sufficient energy for vehicles with a high range. However fuel cells are limited in power density and are not capable of energy recuperation. Therefore it appears to be straightforward to combine the FC with a second, high power, intermediate storage device such as ultracapacitors.

Fuel cell is an electrochemical device and because it is supplied with gas through pumps, valves and compressors, it has large time constants, reaching to several seconds. Consequently, it cannot correctly respond to fast increasing or decreasing power loads, and may be damaged because of repetitive stepped power loads. For this reason, the fuel cell, in the hybrid system, is only operating in nearly steady state conditions, and supercapacitors are functioning during lacking energy from main source, transient energy delivery or transient energy recovery. As we said at the beginning the main weak points of fuel cell is its slow dynamics. To determine the ultracapacitor size we should proceed similar as in fuel cell – battery system. The output power of an ultracapacitor which operate in parallel to a fuel cell must satisfy the maximum power required by traction motor. Since ultracapaciotarele have high specific power and small physical dimensions may be sized bigger then the difference power that fuel cell cannot deliver the traction motor. In this way the fuel cell stress is reduced to zero. The output voltage is given and in this case by the voltage of the main bus of the vehicle. Energy capacity for an ultracapacitor in a hybrid system is not an important parameter because the ultracapacitor is used for high specific power and not for high specific energy. Therefore the ultracapacitors are used in hybrid vehicles where is need by high power for a short period of time. The essence of a fuel cell – ultracapacitor configuration is that the fuel cell works quite close to its maximum power at all times. The implementation of an ultracapacitor storage device allows reducing the size and cost of the fuel cell and provides extra power during acceleration, improving driving comfort. With a booster device the fuel cell can operate most of the time at moderate power, which increases its efficiency and thus results in fuel savings. Finally, depending on the actual driving mode, recuperation of braking energy will also contribute to fuel savings.

D. Fuel cell – battery – ultracapacitor

As we saw before batteries and ultracapacitors both offer unique advantages as secondary energy sources for hybrid electric vehicles. In fact, the high specific power, high efficiency and long lifetime of ultracapacitors are excellent complements to the high specific energy of Li-Ion batteries. Thus, a combined energy storage system has the potential to maximize the advantages of each technology, while minimizing the disadvantages [9].

IV. CONCLUSION

The main objective of this paper is to present briefly the main equipments and the main configurations of power supply and energy storage systems for total electric hybrid vehicles. The usefulness of these systems and configurations is maximal and can certainly make the road transport totally ecological. As seen these configurations offers multiple possibilities for the development of electric vehicles. The most important possible configurations have been presented along with advantages and disadvantages of each. Currently the biggest restriction is given by technology which is still in its early stages and the high price of equipments. Important is that research in this area continues and is upward being favored and by environmental legislation.

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