



ANALYSIS OF HIGH VOLTAGE BATTERY FOR HYBRID, PHEVS & ELECTRIC VEHICLE APPLICATION

Dr. Suhas B. Dhande

Director, K.R. Sapkal College of Management Studies (Savitribai Phule Pune University).

ABSTRACT

The limited sources of fossil fuels and emergence to reduce greenhouse emissions are the forcing factors for alternate sustainable propulsion technologies. The automotive emission norms are becoming stringent. Euro V & Euro VI norms are forcing all automotive manufacturers to push fuel economy on the higher side and CO₂ on the lower side. Diesel technologies are almost reached to its peak performance. On the other side, various renewable energy sources are not yet fully developed or commercialized. Till that time, hybrid propulsion technology is the interim solution for automotive.

High voltage battery is the one of the critical components in hybrid architecture and selection of the battery technology is even more critical. Lead acid batteries are stable in automotive, Ni-MH is also about to settle in hybrid vehicles. Though Ni-MH HV battery has its own limitation, but the advantages are more compared to other technologies as on date. But it has very low potential to take it forward to PHEVs & EVs. So the researchers are working on various other technologies. Li-Ion is one of the most prominent players. Ultracapacitors are also has shown prospects. This paper attempts to explore the exact need and pros and cons of various HV battery technologies so that it can help automotive manufacturers' decision-making process. Further, it can be helpful to the researcher and battery manufacturers for the future path.

KEYWORDS: High Voltage Battery, PHEV, Electric Vehicle, Ni-MH, Li-Ion.

Introduction:

Kyoto Protocol regulations were designed to reduce greenhouse gas emissions. That did not affect the automobile industry directly, though it was a major focus as automotive accounted for more than 30% of greenhouse gas emissions and expected to grow even more significantly. The Kyoto protocol allows developed countries to achieve cost-effective greenhouse gas emission reductions abroad by means of international emissions trading (IET), joint implementation (JI) and the clean development mechanism (CDM). The article argues that JI and CDM projects will be more effective, efficient and politically acceptable than an IET system (Woerdman, 2000)

Since 1769, after the invention of steam-propelled vehicles by Nicholas Cugont, the growth of automobile industry is remarkable, following the invention of gasoline powered IC engine to electronic engine management systems by Bosch. A comprehensive systems approach is essential for effective decision making with regard to global sustainability since industrial, social, and ecological systems are closely linked. Despite efforts to reduce unsustainability, global resource consumption continues to grow. There is an urgent need for a better understanding of the dynamic, adaptive behavior of complex systems and their resilience in the face of disruptions, recognizing that steady-state sustainability models are simplistic (Fiksel, 2006). In recent years, the automobile industry had experienced a spur of new technologies viz. hybrid, mibrid, tribrid technologies. While the hybrid is a combination of traditional gasoline engine and battery-powered electric motor, mibrid (mild hybrid) had a diesel-electric engine and tribrid had three energy sources- gasoline, electricity and hydrogen. Despite the fact that the idea of a hybrid is popular since many years in automobiles, the process of serious product development is in place now. Hybrid-electric vehicles have experienced a significant rate of growth in the last 10 years. This is remarkable since the automotive sector is typically averse to the more radical technological change of engines (Dijk & Yarime, 2010). The capacity of eco-innovations to provide new business opportunities and contribute to the transformation towards a sustainable society depends on the interplay of those dimensions and the engagement of key stakeholders in the innovation process (Carrillo-Hermosilla, Rio, & Könnölä, 2010)

The article explores several fundamental questions as below:

1. What is the current state of scientific knowledge about HV (High Voltage) battery technology essential for hybrid vehicles?
2. What scientific advances are required to better understand the technologies and their future?
3. How can this knowledge be applied to the design and development of HV battery for hybrid and electric vehicles?

Background: High Voltage Battery for HEV / PHEV / EV Application

Most preferred batteries for xEV application are Nickel Metal Hydride (Ni-MH) because of the safety aspect. Presently it is the most widely used battery for xEV

applications. They have reached a matured stage of development. Hence, many OEMs are using Ni-MH batteries in their current production as well as demonstrator vehicles (Srinivas, Prasad, Satish, Dhande, & al., 2009). Lithium Ion (Li-Ion) technology is the strongest candidate against Ni-MH due to its high energy potential. Li-Ion is the most widely used battery technology for electronic goods. It also has huge potential for xEV applications. But the unfavorable factors are cost and safety. Toyota and Honda believe battery technology has not advanced far enough to make electric cars practical and are focusing their efforts on making gasoline-electric hybrid vehicles ... more fuel efficient and affordable.” (Shirouzu, 2009). Li-Ion batteries should be used within safe temperature and voltage ranges in order to operate safely and efficiently. (Lu, Han, Li, HUa, & Ouyang, 2013)

Battery Terminologies and critical functional aspects

- Packaging
- Rating
- Life
- Monitoring Variables

Cell: This is where the chemical reaction happens. A cell typically consists of an anode, cathode, and electrolyte.

Module: Cells are connected in series/parallel to form modules.

Battery Pack: A battery pack typically consists of the following “please see figure 1”

- Modules
- BMS
- Cooling system
- Sensors
- Contactors
- Service plug

Two Important Specs of a Battery

Energy :

Specific energy defined as the energy content per unit mass of the battery.

Unit: Wh/kg

- Energy density is energy content per volume

Unit: Wh/L

- kWh/Ah Rating: It represents the total energy content in a battery pack.

Energy translates to the range of a vehicle. This should be high for EV and PHEV.

Specific Energy:

Ni-MH:40 Wh/kg

Li-Ion:60-80 Wh/kg

Power :

- Specific power is power capacity per mass

Unit: W/kg

- Power density is the power capacity per volume

Unit: W/L

Power translates into torque and acceleration. This should be high for HEV.

- kW Rating: It is the charging and discharging power capacity of a battery pack

Battery Life

- Calendar Life: Life of a battery in terms of duration of use.

unit: No. of years

Cycle Life:

- Micro cycle life: no. of charge-discharge cycle possible within a small range of SOC.

This is important for HEVs

- Full cycle life: no. of charge and discharge cycle possible within a full range of SOC.

This is important for Evs

- PHEVs should have good micro and full cycle life.

Shelf Life: The life of a battery starts decreasing from the time of its manufacturing irrespective of whether it is used or not. Shelf life is the life of a battery from the date of manufacturing.

State Of Charge (SOC): SOC represents the amount of energy left in a battery. It is equivalent to Fuel Gauge for a conventional vehicle.

- Expressed in Percentage.
- 0% completely discharged
- 100 % fully charged

State Of Health (SOH): It is the measure of the condition of the battery.

- Typically, a battery's SOH will be 100% at the time of manufacture and will decrease over time and use

Depth Of Discharge (DOD): It is an alternate method to indicated batteries SOC. It is an inverse of SOC.

- 100% DOD represents a fully discharged battery.

Battery Management System (BMS): This is a controller which is part of a battery pack. It controls the complete functioning of the battery.

Functions of BMS

- Monitoring: active monitoring of various parameter at cell, module and pack level,
- Computation
- Communication
- Protection: BMS is programmed to protect the battery from fault conditions
- Optimization

Electrochemistry

- Ni-MH (Nickel Metal Hydride)
- Li-Ion (Lithium Ion)

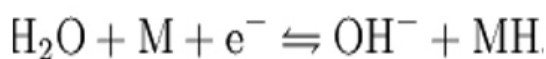
Nickel Metal Hydride Batteries

Cathode: Metal Hydride

A compound of rare earth metals like Lanthanum or cerium with nickel, cobalt, manganese, or aluminum.

Anode: Nickel Hydroxide

Electrolyte: Potassium Hydroxide



Li-Ion has many technologies with different anodes and cathodes as shown in "table 1". The electrochemistry of Li-Ion battery is described in "figure 2".

Advantages of Li-Ion batteries

- High Voltage: It produces 3.6 volts, approximately three times the voltage of

Ni-MH batteries. This will make it possible to make smaller and lighter equipment.

- High energy density: It is because of their high voltage and lightweight features they boast a higher energy density than Ni-MH batteries.
- No memory effect
- Flat discharge Voltage: That is allowing the production of stable power throughout the discharge period of the battery.

The comparison of various battery technologies is shown in "table 2" on various parameter.

The "table 4" shows various goal categories of HV battery and their importance in terms of vehicular requirement. The "figure 3" shows how the requirement of battery duty cycle changes depending upon the vehicular application.

Mechanism to increase lifetime include

- Advanced anodes
- Operation of battery within a small state of charge window
- Operation of battery at reduced rate of discharge

Mechanism to improve safety include:

- Operation of battery within a small state of charge window
- The operation of battery at reduced rate of discharge.
- Addition of extra safety devices and control systems

Mechanism to improve Power Density include:

- Increase surface area of electrode
- Operation at high rates of discharge

Mechanism to reduce cost include:

- Inexpensive electrodes
- Inexpensive packaging and safety mechanism
- New manufacturing processes
- Manufacturing economies of scale

Mechanisms to increase energy density:

- Thicker electrode materials
- New electrode chemistries

Industry Analysis

- Major Players
- Cost analysis
- Future trends

When a research was undertaken to understand how the research between the HV battery manufacturers and the OEMs collaborates, the relationship came on the surface. Most of the battery manufacturers have partnerships with the OEMs for the HV battery development for vehicular application. Some of the partnerships are as shown in "figure 4".

A Case Study On Tesla Roadster (Battery system)

Tesla Roadster Battery System

Technology : Nickel-based Lithium Ion chemistry

Performance:

- Acceleration: 0 to 97 kmph in under 4 seconds.
- Top Speed: 210 kmph
- Range: 346 Km

Battery :

- Nominal voltage: 375 Volts.
- Energy capacity: 53 kWh.
- Power Capacity: 200kW.
- The battery cell is called 18650 because of its 18 mm diameter and 65 mm length.
- There are 6800 such cells.
- Weight: 450kg.
- Full charging time: 3.5 hours
- The Battery is supplying 185kW, 375Nm Motor, max speed 14000 rpm.

Safety Features :

Cell and Module level:

- Positive temperature coefficient limiting device.
- Current Interrupt Device (CID)
- Packaged in steel cans
- Each of the cells has fuses
- There are 11 battery modules and each has its own controller for monitoring voltage and temperature.
- Cooling circuit across each cell provides better thermal management.
- The smaller cell provides large surface area for cooling.

Battery Pack Level

- The following sensors are present in a battery pack.
- Crash sensor
- Vehicle orientation to the ground (to detect a rollover)
- Smoke
- Humidity and moisture
- The BMS monitors and control current, voltage, temperature etc
- Ability to disconnect the HV battery system from the rest of the vehicle if any of a number if adverse conditions are detected.
- None of the HV system components are accessible to accidental contact.
- HV system is enclosed, labeled and color coded.
- The energy stored in a Tesla Roadster battery pack is equivalent to 8 liters of petrol
- Battery cost - @ 12,000-14,000\$

Conclusion:

Euro V & Euro VI norms had forced hybrid propulsion technology as the interim solution for automobility, till the time renewable sources are fully commercialized. (High voltage) HV battery is the one of the critical components in hybrid architecture and selection of the battery technology is even more critical. Supercapacitors and Lead acid batteries are having very limited automotive use in terms of hybrid, PHEV & EVs. Ni-MH is quite widely used in hybrid vehicles. Though it has its own limitation, but the advantages are more compared to other technologies as on date. But it has very low potential to take it forward to PHEVs & EVs. So the researchers are working on various other technologies.

Li-Ion is one of the most prominent players. It has wide potential but the same time it has many challenges to overcome like safety, cost, and longevity. When exposed to high heat, external as well as internally by the battery itself, Li-Ion can suffer from an event called thermal runaway, a feedback loop of ever-increasing temperature that can often result in catching fire. The cost of Li-Ion batteries is currently very high as compared to Ni-MH but can be brought down once met economies of scale. Further, Ni-MH can be returned to 95% of original capacity even after fault, which not the case with Li-Ion and hence only replacement is the option which is very costly.

Still, Li-Ion looks to be the promising battery for PHEV and EV application as many manufacturers and researchers are working hard to make it safe and commercially viable. It seems to be the prospective technology and the future of automotive High Voltage batteries.

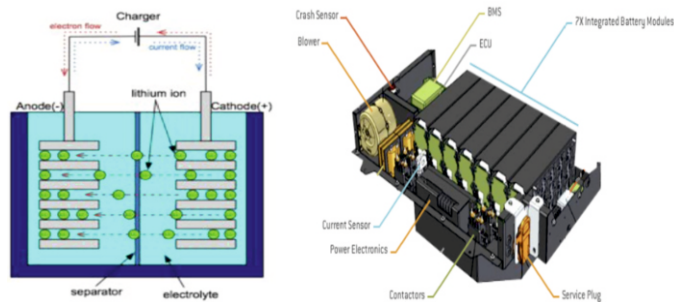


Figure 1: HV Battery construction

Table 1: Li-ion Technology

Many Anodes are possible	Many electrolytes are possible	Many cathodes are possible
Carbon/Graphite Titanate Titanium Oxide based Thin Oxide based Tungsten oxide Silicon	based Various solid electrolyte Polymer electrolytes	Cobalt Oxide Manganese oxide Mixed oxide with Nickel Iron Phosphate Vanadium Oxide based Nickel-cobalt-manganese

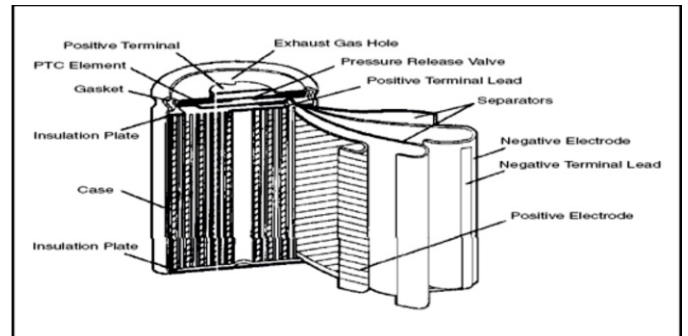
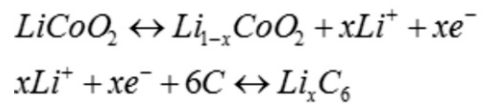
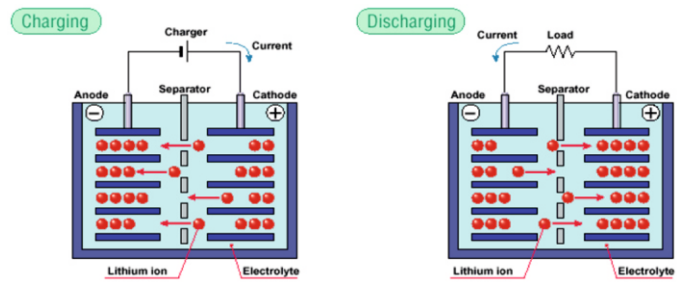


Figure 2: Electrochemistry

Table 2: Battery Technology Comparison

PARAMETER	Lead-Acid	Ni-MH	Li-Ion	Ultracap
Nominal cell voltage (V)	2	1.2	3.6	1.8
Specific Energy, Wh/kg	25	40	60 to 80	5
Battery/Module specific power, 10 sec, W/kg				
23 deg C, 50% SOC	400	1300	3000	>3000
-20 deg C, 50% SOC	250	250	400	>500
Charge acceptance, 10 sec, W/kg				
23 deg C, 50% SOC	200	1200	2000	>3000
2010 Projected Cost>100,000 per year				
\$kWh, Module	100	500	700	20000
\$kWh, Full pack	140	600	1100	25000
\$kW, pack	9	18	22	40
Energy Efficiency	Good	Moderat	Good	Very
Thermal Managements requirements	Light	Moderate	Hign	Light
Electrical control	Light	Moderate	Tight	Tight

The relative comparison of the battery technologies is shown in "table 3" on various parameter.

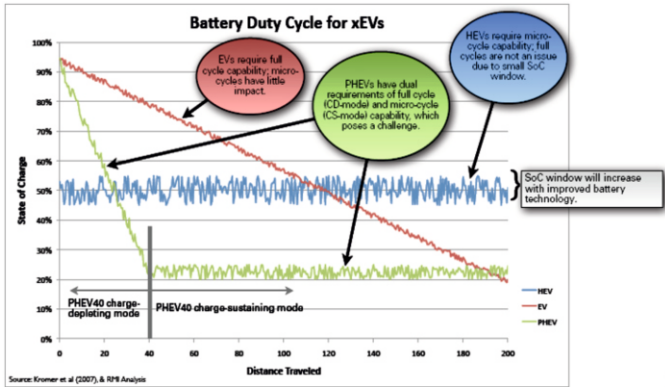
Table 3: Attribute comparison

Attribute	Lead Acid	NiMH	Li-Ion
Weight (kg)	Poor	Fair	Good
Volume (lit)	Poor	Fair	Good
Capacity/Energy (kWh)	Poor	Fair	Good
Discharge Power (kW)	Poor	Fair	Good
Regen Power (kW)	Poor	Fair	Good
Cold-Temperature (kWh & kW)	Poor	Fair	Good
Shallow Cycle Life (number)	Poor	Fair	Good
Deep Cycle Life (number)	Poor	Fair	Good
Calendar Life (years)	Poor	Fair	Good
Cost (\$/kW or \$/kWh)	Poor	Fair	Good
Safety- Abuse Tolerance	Poor	Fair	Good
Maturity - Technology	Poor	Fair	Good
Maturity - Manufacturing	Poor	Fair	Good

Key (relative to each other)
 Poor
 Fair
 Good

Table 4: Five Goal Categories Must be Met for xEV Energy Storage

Category	Description	Why It's Important
Energy	Specific energy is the energy capacity per mass (Wh/kg). Energy density is the energy capacity per volume (Wh/L).	Energy translates into vehicle range. High energy is needed to provide adequate range within weight and space constraints. This is more important for PHEVs and EVs than for HEVs.
Power	Specific power is power capacity per mass (W/kg). Power density is the power capacity per volume (W/L).	Power translates into torque and acceleration. High power is needed to provide adequate boost in HEV applications. Power density is less important in PHEV & EV applications due to their larger high-energy battery.
Cost	Cost is most often discussed in per-energy (\$/kWh) and per-power (\$/kW) terms. The context (cell-level vs. pack-level) should be considered when discussing cost.	Cost is one of the largest obstacles to the commercialization of PHEVs and EVs. Energy storage cost represents a significant portion of vehicle cost for PHEVs and EVs, and must be reduced for these vehicles to become cost-competitive with traditional vehicles.
Lifetime	Lifetime is considered in terms of calendar-life and cycle-life. Cycle-life is further defined in terms of micro-cycles (small changes in SoC) and full-cycles (full discharge/charge).	HEVs operate in charge-sustaining mode and require sufficient micro-cycle lifetime. EVs operate in charge-depleting mode and require sufficient full-cycle lifetime. PHEVs have perhaps the most difficult requirements, requiring both micro- and full-cycle lifetimes. All vehicles require sufficient calendar life (15 years).
Safety	There are numerous aspects to safety, including operating temperature range, heat generation, and response to overcharging, short circuit, mechanical damage, etc.	Safety is important for the obvious reason that certain battery failure modes in automotive applications could be catastrophic.



(Kromer & Heywood, 2007)

Figure 3: Battery requirement differ by application

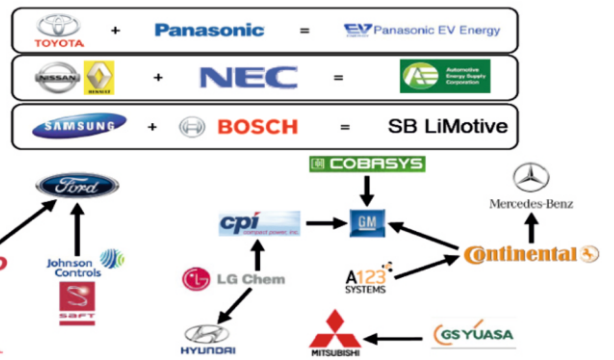


Figure 4: Automakers and Battery Companies are Forming Partnerships

REFERENCES:

- Carrillo-Hermosilla, J., Rio, P. d., & Könnölä, T. (2010). Diversity of eco-innovations: Reflections from selected case studies. *Journal of Cleaner Production*, 1073-1083.
- Dijk, M., & Yarime, M. (2010). The emergence of hybrid-electric cars: Innovation path creation through co-evolution of supply and demand. *Technological Forecasting and Social Change*, 1371-1390.
- Fiksel, J. (2006). Sustainability and resilience: toward a systems approach. *Sustainability: Science, Practice, & Policy*, 8.
- Kromer, M., & Heywood, J. (2007). Electric Powertrains: Opportunities and Challenges in the U.S. Light-Duty Vehicle Fleet. *Sloan Laboratory, Massachusetts Institute of Technology*, 5.
- Lu, L., Han, X., Li, J., HUa, J., & Ouyang, M. (2013). A review on the key issues for lithium-ion battery management in electric vehicles. *Journal of Power Sources*, 226-272.
- Shirouzu, N. (2009). Technology Levels Playing Field in Race to Make Electric Car. *The Wall Street Journal*, 4.
- Srinivas, A., Prasad, T., Satish, T., Dhande, S., & al., e. (2009). Diesel Hybrids - The Logical Path towards Hybridisation. *SAE International*, 10.
- Woerdman, E. (2000). Implementing the Kyoto protocol: why JI and CDM show more promise than international emissions trading. *Energy Policy*, 29-38.