

VOLTEC Battery System for Electric Vehicle with Extended Range

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ABSTRACT

Mid 2006 a study group at General Motors developed the concept for the electric vehicle with extended range (EREV). The electric propulsion system should receive the electrical energy from a rechargeable energy storage system (RESS) and/or an auxiliary power unit (APU) which could either be a hydrogen fuel cell or an internal combustion engine (ICE) driven generator. The study result was the Chevrolet VOLT concept car in the North American Auto Show in Detroit in 2007.

The paper describes the requirements, concepts, development and the performance of the battery used as RESS for the ICE type VOLTEC propulsion system version of the Chevrolet Volt.

The key requirement for the RESS is to provide energy to drive an electric vehicle with “no compromised performance” for 40 miles. Extended Range Mode allows for this experience to continue beyond 40 miles. Multiple factors helped refine a requirement of at least 8 kWh usable energy, and 115 kW discharge power over the applied battery state of charge range. The Chevrolet Volt vehicle is based on GM's global compact vehicle platform. Aggressive targets for mass, volume, and timing have been considered for impact beyond start of production (4Q2010).

A battery cell providing both, very high energy density and high power density at the same time had to be developed and validated applying the latest Li-Ion technology.

Integration into the car should allow for good aerodynamics, provide the best crash protection and have low impact on customer useable space. The battery must also be able to perform in all typical automotive atmospheric conditions. An inter-cell thermal system was sized and balanced, to efficiently manage temperatures within the battery and help lengthen battery life.

New tests and methods had been developed for battery systems development in the lab, in the vehicle and in models. Data and examples will be shared. Specific vehicle/battery test activities will be introduced. Finally performance results demonstrating the characteristic(s) of the system will be shown.

INTRODUCTION

Electric Vehicle with extended range a new vehicle class

A vehicle that functions as a full-capability electric vehicle when energy is available from a rechargeable energy storage system (RESS), e.g. a high voltage battery and having an auxiliary energy supply that is only engaged when the battery energy is not available is called Electric Vehicle with extended range (EREV).



Figure 1. Chevrolet Volt Concept car 2007

An EREV can travel the initial range electrically with energy from the “plug-in” charged battery and additional range based on a second fuel (e.g. Gasoline, E 85, Diesel, Hydrogen, CNG) converted by an engine generator set or a fuel cell system. The first operation phase is called electric vehicle mode and represents charge depletion for the electrical energy storage, the second phase is called extended range mode and the energy storage system is in charge sustaining mode. In both modes the vehicle performance shall be equal so the vehicle dynamics are not influenced by the mode transition. In the EREV concept the RESS needs to provide the full power for transient operation in charge sustaining and charge depletion mode. The vehicle has to contain two energy storage systems a rechargeable energy storage system and a system for the “second fuel” which could be for example gasoline, Bio-ethanol, Diesel, Hydrogen or natural gas. The RESS provides energy in the charge depletion phase and to support acceleration and regenerative braking in the charge sustaining mode. The vehicle requires a capability to be recharged from an electricity source outside of the vehicle through plug-in. An on-board charger allows the use of the existing electrical infrastructure providing 100V to 240 V outlets in households of most countries.

The intention of the new propulsion system is to generate the maximum miles driven electrically to replace petroleum based energy (gasoline, Diesel) through electric energy, which should be generated from different sources and from renewable energy eventually. Most vehicles are operated less than 64 km (40 miles) per day in the USA and other parts of the world (Europe, Asia), but in many cases longer distances have to be travelled requiring driving range for a single drive of more than 200 km (124 miles) before the driver and the passengers need to stop for human needs. The idea had been, to come up with a concept which covers more than 75% of all driving overall with electric energy and maximize the replacement of petroleum based fuel for cars.

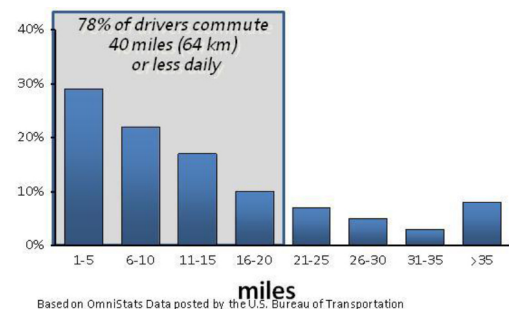
MAIN SECTION

Development of Performance Requirements

When the Chevrolet Volt concept had been developed in the year 2006 a number of key vehicle parameters had been established. Those drove the requirements of the rechargeable energy storage system. The vehicle was intended to set a new standard for electric vehicles in regard to acceleration, durability and customer value. A vehicle that shall meet the needs most drivers, is fun to drive, is energy efficient and very attractive. A vehicle which provides access to alternative energy sources and options to deal with increasing uncertainty of affordable supply of gasoline. A vehicle making a step toward sustainable individual transportation.

Vehicle Range

Studies of General Motors based on the real customer usage information provided by the Federal Highway Association and the Southern California Association of Governments (SCAG) -Regional Travel Survey (RTS)[1] showed that 80% of the petroleum can be replaced by vehicles capable of 40 miles electric range. In addition sufficient energy (second source) for longer trips should be stored in the vehicle to make the vehicle usable for all trips. 300 miles for an extended range trip followed by the option to refuel the car in 3 minutes or recharge it with electric power make the vehicle capable to be the single car for every driver.

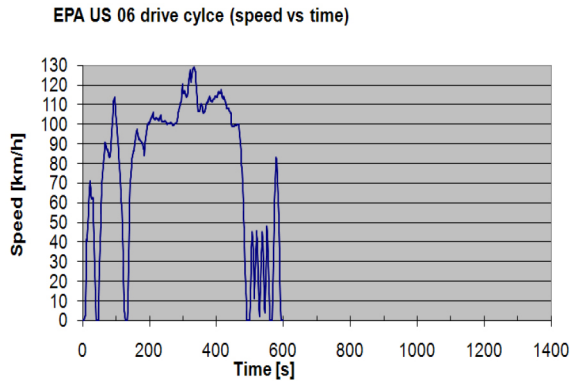


Graph 1. Typical one-way miles from home to work

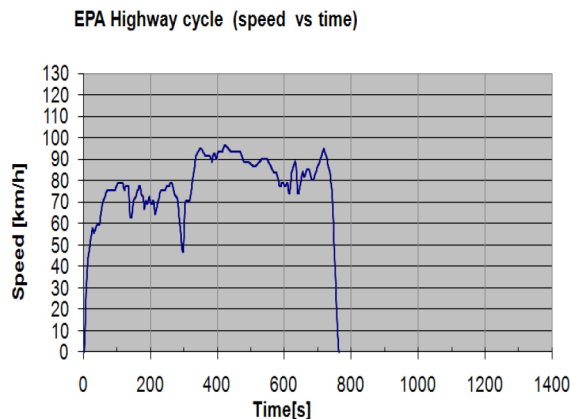
Energy (Electric)

The amount of energy stored depends on the range required (km or miles) and the energy consumption (Wh/km). The energy consumption of a vehicle is dependent on vehicle characteristics (Drag resistance, rolling resistance, mass, propulsion efficiency), the driving style (acceleration, speed, profile), the ambient conditions (temperature, sunshine, rain) and the topographic profile. Driving Style can be represented by drive cycles, for example the EPA (Environmental Protection Agency) urban-, highway- or US06 drive cycle. The urban drive cycle with an average speed of 32 km/h and a top speed of 90 km/h represents the low end of performance and energy use for an electric vehicle, the US06 drive cycle

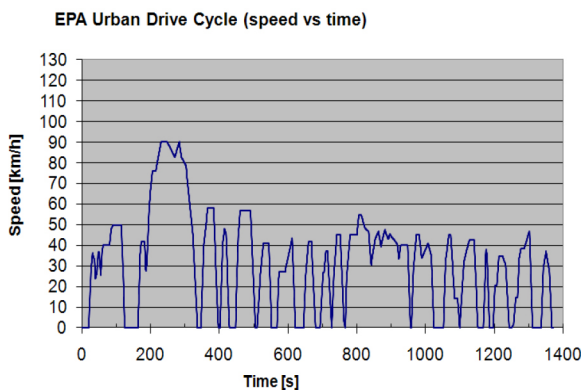
with an average speed and 77 km/h and a top speed of 129.2 km/h represents a faster, more dynamic driving style requiring more power and more energy use per mile. The Urban drive cycle represents only a few percent of all driving recorded in the regional travel survey of the SCAG. The power required for the US 06 cycle would cover more than 90% of all drives in the study.



Graph 2. US06 drive cycle: Speed versus time



Graph 3. Highway drive Cycle: Speed versus time of the



Graph 4. Urban drive cycle: Speed versus time

The vehicle requirement had been defined as 40 miles (64 km) electric range in urban driving style. To develop the specifications toward energy for the rechargeable energy storage systems, simulations of the EPA drive cycles and the preliminary Volt vehicle parameters had been performed. The urban drive cycles net 120 Wh/km energy consumption. And the US06 drive cycle required 180 Wh/km. To enable 64 km of driving in the urban drive cycle 8 kWh of energy was needed. Advance Lithium Ion battery systems can achieve energy densities of up to 100 Wh/kg, which is higher than most other storage systems such as electrochemical capacitors. The capacity and energy of a battery will decrease over time as well as through charge and discharge cycles.

Sizing for the total energy of the battery system would depend on 3 factors:

- Useable energy at end of life
- Power requirements over the operating state of charge (SoC) range
- Battery temperature during driving, charging and “off-time”

Considering these effects, and balancing it versus the cost, mass and volume demands, the total begin of life energy requirement of 16 kWh was resolved. This nominal energy was defined for normal conditions (23°C, 1 hour discharge rate C/1)

Range (“second fuel” gasoline)

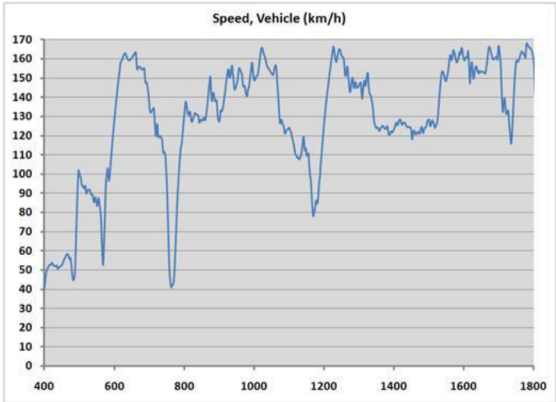
The vehicle has to be capable to drive more than 480 km (300 miles) in extended range mode until refueling the storage system, e.g. gasoline tank. The battery is affected as it still has to provide power for acceleration as well as recapture electric energy during deceleration (“regenerative braking”). Energy is still required to supplement the generator power, but demand is lower than the full propulsion power. In the extended mode, as multiple accelerations are addressed, equivalent charge by the generator or regenerative braking is induced to sustain driving performance. This energy requirement is dependent on the operation strategy of the engine-generator drive unit, which over longer periods would define an energy reserve of 300 to 600 Wh.

Vehicle Performance

Appealing performance had been an early attribute of the Chevrolet Volt, expressed by a targeted acceleration time of less than 9 seconds from 0 km/h to 97 km/h (0 to 60 miles per hour). Passing performance measured as the acceleration time from 80 km/h to 120 km/h (50 mph to 75 mph), this is referenced as elasticity, and is an important metric in Europe. Other vehicle performance attributes that were dependent upon battery power were top speed and speed at grade. The vehicle has to be able to accelerate to 160 km/h (99 mph) and sustain this velocity continuously. For a grade of 6%, the speed of 112 km/h (7 mph) should be maintained over several

km's or miles. This emulates ascent of interstate highways in mountainous areas.

The Chevrolet Volt has to be able to perform the US06 drive schedule in charge depletion and charge sustaining modes. It must be capable of Autobahn environments, where it is typical to drive up to 160 km/h. A recorded speed trace from typical German Autobahn test drive is shown in [figure 5](#).



Graph 5. Electric vehicle on the German Autobahn: Speed(km/h) over time (s)

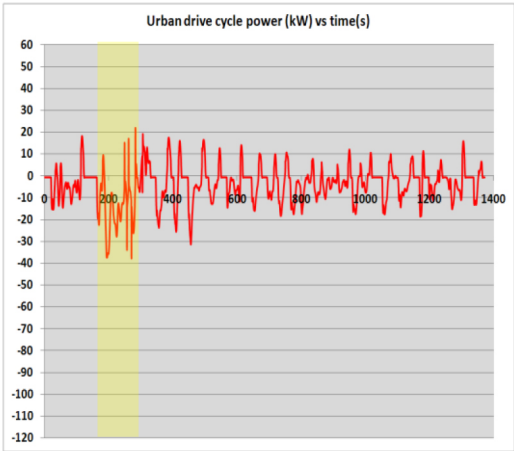
It may not be obvious that the speed trace is influenced by traffic, speed limit and road layout. In addition the topographic profile, not shown, will impact the power consumption. Comparison of the 3 emission based drive cycles and the recorded Autobahn data, show that a system has to meet real world power requirements, in addition to the emission based drive cycles. The root mean square value of the power (P_{rms}) is a measure for the usage of the battery and its relation to the defined schedule.

Table 1. US emission cycles in comparison, in addition real drive data.

	Duration	Distance	Speed	Distance	Speed	CD	CS
	s	km	km/h	Miles	mph	P_{rms}	P_{rms}
						kW	kW
US06	600 s	13 km	77 km/h	8.02	48.1	27.4 kW	24.9 kW
Hwy	765 s	16 km	76 km/h	10.1	47.5	13.0 kW	8.6 kW
Urban	1372 s	12 km	32 km/h	7.5	19.7	9.0 kW	9.8 kW
Autobahn							
example	600 s	19 km	114 km/h	11.8	70.7	37.7 kW	24.5 kW

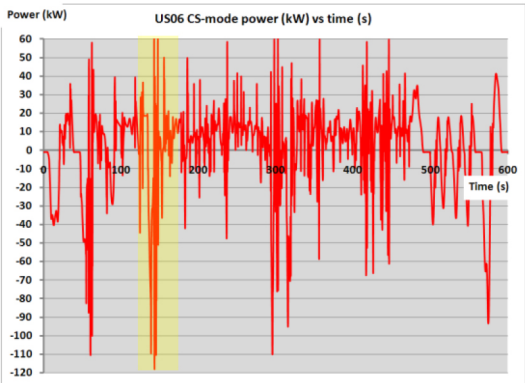
Battery Discharge Power

The urban drive cycle based power profile does only require up to 40 kW peak discharge power.



Graph 6. Urban Drive Cycle: Power (kW) over time (s)

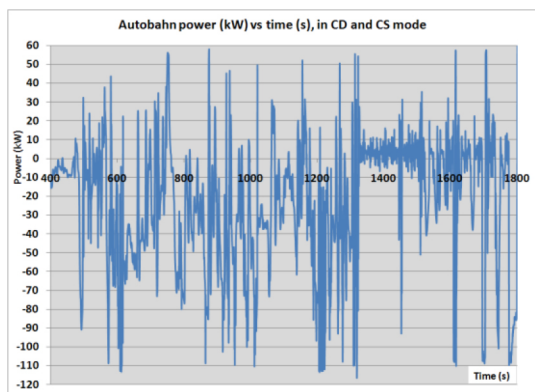
To perform the US06 drive cycle, in charge depletion and sustaining mode, and achieve acceptable vehicle acceleration, the battery peak discharge power was established as 115 kW.



Graph 7. US06 drive cycle: battery power over time

The Autobahn power trace shows a higher power demand, and longer durations, but still satisfied by previously defined requirements.

As a reference point, performance shall be met when the battery is at temperatures above 20°C. Based on anticipated behavior in other ambient conditions, for instance, 10°C, 0°C and -25°C, the team was able to constrain the selection of the battery chemistry and system design.



Graph 8. Electric vehicle Autobahn in Germany, power profile in CD and CS mode.

Battery Charge Power (plug-in)

Energy from the electric grid shall be used as much as possible. The vehicle integrated on-board charge module (OBCM) is designed for level 1 (120V AC single phase 12 A) and level 2 (240V AC 15 A) charging. The resulting wall consumption could ramp up to either 1.2 kW or 3.2 kW as DC charge power demands are directed by on board electronics. The DC power, however, will depend on the actual input AC voltage. Charge duration can vary from 3.5 hours up to 10 hours, depending on AC supply voltage, auxiliary power use, temperature, and beginning SOC. The battery charge rate can vary from 0.2 C down to 0.05 C rate (C-rate = nominal capacity /1 hour).

Battery charge power (Regenerative)

During regenerative braking charge power of up to 60 kW can be directed to the battery. This represents a charge rate of almost 4 C. Longer downhill braking and may see transient operation of up to 60 kW shall be captured for up to 10 seconds when the battery temperature is above 20°C. During Charge Sustaining operation the battery has to be able to be charged with 60 kWh and provide up to 115 kW discharge power.

Electrical Interface

The Battery system would have separated high voltage (HV) and low voltage (LV) interfaces. All high voltage connections include a high voltage interlock loop (HVIL), which will induce contactors to open when pack is being serviced.

High voltage interfaces are:

- Connector for traction inverter
 - Maximum current 400 A for 30 sec
 - Maximum continuous current I_{rms} 135 A for 60 minutes
 - Maximum Voltage compatibility 420 V

- Connector for on-board charger module

- Connector for auxiliary power module (APM) Manual service disconnect, which allows manual intervention of the series string of cells, within the battery.

Low voltage connectors include:

- 12 V power for battery sensors and controllers
- 12 V power for contactors, wakeup and HVIL
- CAN-bus for battery controls

Life

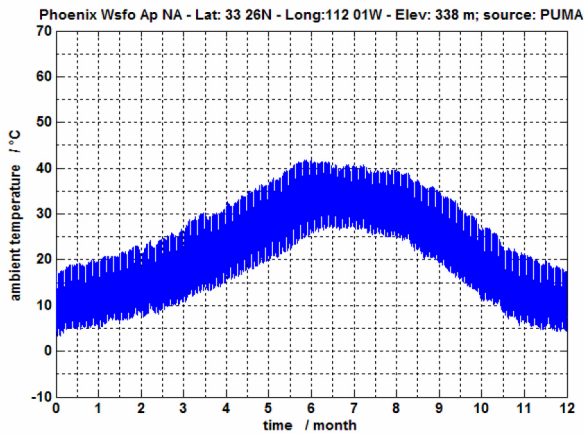
Due to the high value of the battery system, the design intent was for a 10 year life and 240 000 km (150 000 miles) in vehicle performance is required. Batteries have the characteristic of degradation over discharge/charge cycles and time. The capacity degradation may have an effect on range. Over time, the charge sustaining range could decline, but the generator can compensate this effect for the driver. The internal resistance could also increase over time. Exposure to this effect can be avoided by over sizing the battery, so that at beginning of life, battery provides more than adequate power that is governed. As pack approaches its end of life, constraints are relaxed to provide sufficient power. Degradation is also accelerated at elevated temperature. Over the vehicle life, one might expect, more than 5000 full charge depletion cycles and additional charge sustaining. The conservative assumption for battery usage is 80 % of distance driven in charge depletion mode and 20 % in charge sustaining. The actual cycle number can vary as electric range can vary between 40 km and 80 km (25 and 50 miles) as a result of driving style and ambient temperature conditions.

Automotive Requirements

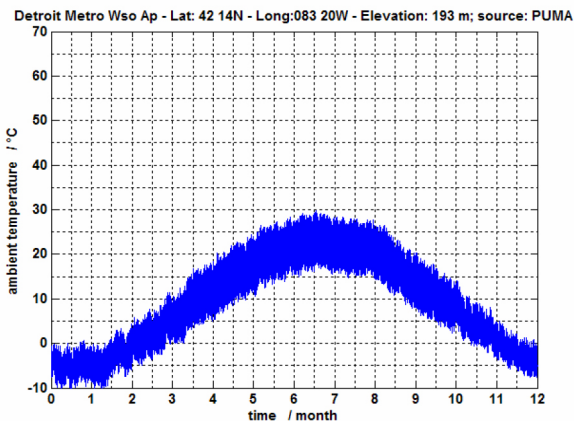
Operating Temperature

Automotive systems have to operate over a wide temperature range. The battery system would need to meet the US06 driving cycle performance from 0°C to 32°C battery temperature and still be operational from -25°C to 52°C ambient temperature. Exposure or storage shall be possible in the range of -40°C to 55°C. This impacts the requirements of all sub-components like the electronic control systems, electrical/mechanical actuators such as main contactors, and the housing of all RESS components. The system would have to perform over many years in areas similar to Phoenix or in Detroit. Phoenix represents a challenge as the high temperatures and sun radiation can drive battery temperatures into degradation ranges. In Detroit, over a long period, the temperatures could fall below 0°C. At low temperatures the

system power can be reduced and battery life preserved to avoid lithium plating.



Graph 9. Average Temperatures for Phoenix, Arizona



Graph 10. Average Temperatures for Detroit, Michigan

Altitude

Driving in high altitude requires the battery system to be able to operate down to 59 kPa ambient pressure. Transition back to normal ambient (102 kPa), within 15 minutes, must also be achievable, without effect on the battery sealing integrity.

Water (flooded road, Carwash)

The vehicle has to be capable of driving in all weather and road conditions. This includes the flooded road and car wash with underbody spray. To meet this vehicle requirement the system has perform under standards close to the IEC class of IP6K9K for water protection.

Vibration & Shock

Vibration profiles and mechanical shock exposure caused by road conditions and installation conditions in vehicle have

been modeled. The battery system has to perform worst case vibration profiles without degradation.

Vehicle Integration (Physical)

Mass & Volume

As in most electric cars, battery system is a major contributor to vehicle mass. To enable the Chevrolet VOLT to evaluate its efficiencies and support vehicle dynamics, the initial mass target for battery system had been set to 160 kg. As the battery structure became more of a vehicle structural element, the equivalent part weights were integrated into the design target numbers and revised to 180 kg later to 190 kg. The vehicle concept of the Chevrolet VOLT required ample space for four persons and a large luggage space. The battery pack should be designed as compact as possible. To meet these requirements the battery pack system a volume target given was 140 dm³.

Crash

The vehicle would also perform all FMVSS and ECE crash tests. Before, during and after these barrier events, the battery system should not expose high voltage or gaseous emissions into the occupant cabin. The team had decided the most optimal battery location was to be outside of crushable zones. Centered on vehicle, fore/aft and side to side, pack was also to be loaded from under vehicle below the cabin floor. Due to this packaging, an additional layer of separation between battery system, passenger compartment, and underbody components was developed in the form of a cover.

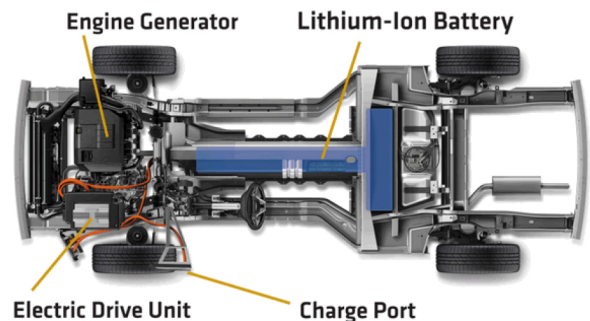


Figure 2. Position of VOLTEC Battery System in Chassis

Vehicle Assembly

The battery system shall be installed at one station in a normal GM vehicle assembly line. It is required to fulfill every assembly step within 60 seconds.