ELECTRIC VEHICLE BATTERY SYSTEMS

To Anju, Anita, and Aarti

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1 ELECTRIC VEHICLE BATTERIES

Road vehicles emit significant air-borne pollution, including 18% of America's suspended particulates, 27% of the volatile organic compounds, 28% of Pb, 32% of nitrogen oxides, and 62% of CO. Vehicles also release 25% of America's energy-related CO_2, the principle greenhouse gas. World pollution numbers continue to grow even more rapidly as millions of people gain access to public and personal transportation.

Electrification of our energy economy and the rise of automotive transportation are two of the most significant technological revolutions of the twentieth century. Exemplifying this massive change in the lifestyle due to growth in fossil energy supplies. From negligible energy markets in the 1900, electrical generation now accounts for 34% of the primary energy consumption in the United States, while transportation consumes 27% of the energy supply. Increased fossil fuel use has financed energy expansions: coal and natural gas provide more than 65% of the energy used to generate the nation's electricity, while refined crude oil fuels virtually all the 250 million vehicles now cruising the U.S. roadways. Renewable energy, however, provides less than 2% of the energy used in either market.

The electricity and transportation energy revolution of the 1900s has affected several different and large non-overlapping markets. Electricity is used extensively in the commercial, industrial and residential sectors, but it barely supplies an iota of energy to the transportation markets. On the other hand oil contributes only 3% of the energy input for electricity. Oil usage for the purpose of transportation contributes to merely 3% of the energy input for electricity. Oil use for transportation is large and growing. More than two-thirds of the oil consumption in the United States is used for transportation purposes, mostly for cars, trucks, and buses. With aircraft attributing to 14% of the oil consumption, ships and locomotives consume the remaining 5%. Since the United States relies on oil imports, the oil use for transportation sector has surpassed total domestic oil production every year since 1986.

The present rate of reliance and consumption of fossil fuels for electrification or transportation is 100,000 times faster than the rate at which they are being created by natural forces. As the readily exploited fuels continue to be consumed, the fossil fuels are becoming more costly and difficult to extract. In order to transform the demands on the development of energy systems based on renewable resources, it is important to find an alternative to fossil fuels. Little progress has been made in using electricity generated from a centralized power grid for transportation purposes. In 1900, the number of electric cars outnumbered the gasoline cars by almost a factor of two. In addition to being less polluting, the electric cars in 1900 were silent machines. As favorites of the urban social elite, the electric cars were the cars of choice as they did not require the difficult and rather dangerous handcrank starters. This led to the development of electric vehicles (EVs) by more than 100 EV manufacturers.

However, the weight of these vehicles, long recharging time, and poor durability of electric barriers reduced the ability of electric cars to gain a long-term market presence. One pound of gasoline contained a chemical energy equivalent of 100 pounds of Pb-acid batteries. Refueling the car with gasoline required only minutes, supplies of gasoline seemed to be limitless, and the long distance delivery of goods and passengers was relatively cheap and easy. This led to the virtual disappearance of electric cars by 1920.

ELECTRIC VEHICLE OPERATION

The operation of an EV is similar to that of an internal combustion vehicle. An ignition key or numeric keypad is used to power up the vehicle's instrumentation panels and electronic control module (ECM). A gearshift placed in Drive or Reverse engages the vehicle. When the brake pedal is released, the vehicle may creep in a fashion similar to an internal combustion vehicle. When the driver pushes the accelerator pedal, a signal is sent to the ECM, which in turn applies a current and voltage from the battery system to the electric motor that is proportional to the degree to which the accelerator pedal is depressed. The motor in turn applies torque to the EV wheels. Because power/torque curves for electric motors are much broader than those for internal combustion (IC) engines, the acceleration of an EV can be much quicker. Most EVs have a built-in feature called regenerative braking, which comes into play when the accelerator pedal is released or the brake pedal is applied.

This feature captures the vehicle's kinetic energy and routes it through the ECM to the battery pack. Regenerative braking mimics the deceleration effects of an IC engine.

An appealing quality of EVs is that they operate very quietly. For the most part, the handling and operation of commercial EVs is comparable to their internal combustion counterparts.

Electric Vehicle Components

The major components of the EV are an electric motor, an ECM, a traction battery, a battery management system, a smart battery charger, a cabling system, a regenerative braking system, a vehicle body, a frame, EV fluids for cooling, braking, etc., and lubricants. It is important to look at the individual functions of each of these components and how they integrate to operate the vehicle.

Electronic Drive Systems

An EV is propelled by an electric motor. The traction motor is in turn controlled by the engine controller or an electronic control module. Electric motors may be understood through the principles of electromagnetism and physics. In simple terms, an electrical conductor carrying current in the presence of a magnetic field experiences a force (torque) that is proportional to the product of the current and the strength of the magnetic field. Conversely, a conductor that is moved through a magnetic field experiences an induced current. In an electric propulsion system, the electronic control module regulates the amount of current and voltage that the electric motor receives. Operating voltages can be as high as 360 V or higher. The controller takes a signal from the vehicle's accelerator pedal and controls the electric energy provided to the motor, causing the torque to turn the wheels.

There are two major types of electric drive systems: alternating current (AC) and direct current (DC). In the past, DC motors were commonly used for variable-speed applications. Because of recent advances in high-power electronics, however, AC motors are now more widely used for these applications. DC motors are typically easier to control and are less expensive, but they are often larger and heavier than AC motors. At the same time, AC motors and controllers usually have a higher efficiency over a large operational range, but, due to complex electronics, the ECMs are more expensive. Today, both AC and DC technologies can be found in commercial automobiles.

BATTERY BASICS

A battery cell consists of five major components: (1) electrodes—anode and cathode; (2) separators; (3) terminals; (4) electrolyte; and (5) a case or enclosure. Battery cells are grouped together into a single mechanical and electrical unit called a battery module. These modules are electrically connected to form a battery pack, which powers the electronic drive systems.

There are two terminals per battery, one negative and one positive. The electrolyte can be a liquid, gel, or solid material. Traditional batteries, such as lead-acid (Pb-acid), nickel-cadmium (NiCd), and others have used a liquid electrolyte. This electrolyte may either be acidic or alkaline, depending on the type of battery. In many of the advanced batteries under development today for EV applications, the electrolyte is a gel, paste, or resin. Examples of these battery types are advanced sealed Pb-acid, NiMH, and Lithium (Li)-ion batteries. Lithium-polymer batteries, presently under development, have a solid electrolyte. In the most basic terms, a battery is an electrochemical cell in which an electric potential (voltage) is generated at the battery terminals by a difference in potential between the positive and negative electrodes. When an electrical load such as a motor is connected to the battery terminals, an electric circuit is completed, and current is passed through the motor, generating the torque. Outside the battery, current flows from the positive terminal, through the motor, and returns to the negative terminal. As the process continues, the battery delivers its stored energy from a charged to a discharged state. If the electrical load is replaced by an external power source that reverses the flow of the current through the battery, the battery can be charged. This process is used to reform the electrodes to their original chemical state, or full charge.

INTRODUCTION TO ELECTRIC VEHICLE BATTERIES

In the early part of 1900s, the EV design could not compete with the plethora of inventions for the internal combustion engine. The speed and range of the internal combustion engines made them an efficient solution for transportation. By the middle of the 1900s, discussions about the impending oil supplies, the growing demands of fossil fuels began to rekindle the inventions of alternate energy systems and discovery of alternate energy sources. By the mid-1970s, oil shortages led to aggressive development of EV programs. However, a temporarily stable oil supply thereafter and a rather slow advancement in battery charge terminations can be enabled at the same time. The charge electronics uses A/D converters to measure peak voltage to within a 2 mV range. This value is less than 0.6% of the voltage of a battery during charging on a per cell basis.

Alternately, IC makers offer different charge techniques. Charge electronics combines programmable, constant-current based fast charging with overvoltage protection for NiMH batteries. Unlike typical detection methods, such as the $-\Delta V$ or dT/dt methods, the charger controller detects an inflection point d^2V/dt^2. This point is reached by the charged battery at approximately 90% capacity and occurs when the battery voltage increase tends to accelerate. This detection mechanism is NiMH battery friendly as it detects the overcharge process at an early stage.

Upon detection of the inflection point, the charger continues the charge current for another 20-minute period. This is followed by a trickle charge phase to maintain a full charge. In order to prevent an inaccurate voltage measurement, the charging is halted, briefly, while a voltage measurement is taken. In addition, the charge control may include options for automatic predischarge of the battery pack, timed charging, and the choice of use of a switched mode power supply.

CHARGING TECHNOLOGY

With electric vehicles (EVs) comes the EV recharge infrastructure, both for public and private, or domestic use. This infrastructure includes recharging units, ventilation requirements, and electrical safety features suited for both indoor and outdoor charging stations. As an example of the developments, to ensure the safe installation of charging equipment, changes have been made to State of California Building and Electrical codes.

Charging Stations

During EV charging, the charger transforms electricity supplied by the local utility into energy compatible with the vehicle's battery pack voltage requirements. According to the Society of Automotive Engineers (SAE), the complete EV charging system consists of the equipment required to both condition and transfer energy from a constant-frequency, constant-voltage source or network to direct current. The direct current is required for the purpose of charging the battery and/or operating the EV electrical systems (e.g., EV interior preconditioning, traction battery thermal management, onboard vehicle computer). The charger communicates with the battery management system and/or monitor (BMON). The management system and/or BMON in turn calculates how much voltage and current is required to charge the battery system.

Charging is accomplished by passing an electrical current through the battery to reform its active materials into their high-energy charge state. The charging process is basically a reverse of the discharging process. Current is forced to flow back to the traction battery pack. This current initiates a chemical reaction in the opposite direction. The algorithm by which this is achieved differs depending upon the battery type and due to the variations in their chemical compositions.

The EV is connected to the EV supply equipment (EVSE), which, in turn, is connected to the local utility. The National Electrical Code (NEC) defines this equipment as the ungrounded conductors, grounded conductors, equipment grounding conductors, EV couplings and connectors, attachment plugs, and all other fittings, devices, power outlets, or accessories installed specifically for the purpose of delivering energy from the utility wiring to the EV.

For residential or private and most public charging locations, there are two power levels: Level I and Level II. Level I or convenience charging, allows for charging the traction battery pack while the vehicle is connected to a 120 V, 15 A branch circuit. A complete charging cycle takes anywhere from 10 to 15 hours to be completed. This type of charging system uses the common grounded electrical outlets and is used when Level II charging is unavailable. Level II charging takes place while the vehicle is connected to a 240 V, 40 A circuit, dedicated solely for EV traction battery charging purposes only. At the Level II voltage and current levels, a full charge takes from 3 to 8 hours, depending on battery type. In order to sustain the Level II power requirements, EVSE must be hardwired to the premises wiring.

A third power level, Level III is any EVSE with a power rating greater than Level II. Most Level III charging systems are located off the vehicle platforms. Level III charging is defined as the EV equivalent of a commercial gasoline service station. In this case, a Level III charging station can successfully charge an EV in a matter of minutes. To accomplish Level III charging, the equipment must be rated at power levels from 75 to 150 kW. The Level III requires supply circuit to the equipment be rated at 480 V, 3 ϕ and between 90 to 250 A. However, the supply circuit for the Level III charge may be even larger in capacity. The equipment is to be handled by specially trained personnel.

All EV infrastructural equipment, at all power levels, are required to be manufactured and installed in accordance with published standards documents such as: NFPA (NEC Article 625), SAE (J1772, J1773, J2293, others), UL (2202, 2231, 2251, others), IEEE/IEC, FCC (Title 47–Part 15), and several others.

Coupling Types

The EV system will be connected to the vehicle by the general public in all weather conditions. There are currently two primary methods of transferring power to EVs: (1) conductive coupling and (2) inductive coupling.

In the conductive coupling method, connectors use a physical metallic contact to pass electrical energy when they are joined together. Specific EV coupling systems—connectors paired with inlets—have been designed that provide a nonenergized interface to the charger operator. Thus, not only is voltage prevented from being present before the connection is completed, the metallic contacts are completely covered and inaccessible to the operator.

In the inductive coupling method, the coupling system acts as a transformer. AC power is transferred magnetically, or induced, between a primary winding, on the supply side, to a secondary winding, on the vehicle side. This method uses EV infrastructure that converts standard power-line frequency (60 Hz) to high frequency (80,000 to 300,000 Hz), reducing the size of the transformer equipment. The inductive connection is developed primarily for EV applications, though it has been applied to other small appliances.

In both conductive and inductive coupling, the connection process is safe and convenient for all users.

Charging Methods

There are three primary methods of charging EV batteries: (1) constant voltage; (2) constant current; and (3) a combination of the two.

Most EV charging systems use a constant voltage for the initial portion of the charging process, followed by a constant current for the finish. Most of the battery capacity is restored during the constant-voltage portion of the charging cycle. The constant-current portion of the charge cycle, commonly referred to as a trickle charge, serves to slowly top off the battery at a rate sufficiently slow to prevent the off-gassing of either hydrogen or oxygen from the electrolyte.

batteries are operated in enclosed cabinets, without fans or a heating system, the cabinets must be vented or the small emissions of hydrogen will build up to dangerous explosive levels.

In addition, space requirements should also be considered during EV battery pack design. Flooded Pb-acid batteries require 32% more space than their equivalent VRLA battery. The additional space requirements are due to rack requirement and the need to provide space to access the battery for maintenance purposes. Thus when it comes to deciding the most suited Pb-acid battery technology for EVs, the VRLA battery provides the greatest benefits to the user.

COLD-WEATHER IMPACT ON ELECTRIC VEHICLE BATTERY DISCHARGE

As seen with temperature characteristics of the traction battery, low temperature limits the battery discharge and useful available capacity. For commercial viability and customer acceptance, EVs need to operate reliably over a wide climatic range. The cold weather deterioration of range is well known, however, it is important to identify and quantify the causes of battery pack degradation. Once the solutions have been identified, it is important to pursue the solutions to eliminate the causes.

The EV performance under cold temperature conditions is analyzed by installing instrumentation on the vehicle to measure the electrical energy entering and leaving the battery pack. Energy consumed is measured for the system controller, climate or HVAC, and the vehicle accessories.

As part of the early phase of the test plan, it is important to develop a test plan and procedure. The necessary hardware required for the test should be installed to observe the battery capacity and SOC characteristics of the traction battery pack. In addition, it is useful to evaluate the new EV lubricant and tires. Understanding of the winter condition HVAC and accessory loads is also useful in determining the EV performance under cold temperature conditions. While gaining an understanding of the HVAC and accessory loads, it is important to evaluate the correction factors developed during the course of the EV analyses.

The cold weather performance tests are performed at 55 mph driving condition on a level concrete road. The driving profiles used during the performance tests include at least four different drivers with no specific instructions. The battery pack is tested several times during the day of the test. The battery pack tests are then repeated two to three times during the week. All tests of the battery pack performance are terminated when the end-of-test criterion has been reached.

Some of the observations of the cold weather performance on a compact size EV using VRLA batteries are:

1. Aerodynamic drag effect makes a significant impact on cold weather performance. The power required is about 10% higher at 20°F than at 70°F. The aerodynamic drag increases owing to higher air density (for a given drag coefficient) as the battery pack temperature increases.

2. Losses associated with EV lubricants are low at low-operating temperatures. Better performance lubricants are required to reduce the viscous losses.

3. Road traction losses increase under cold weather operating conditions. Newly developed EV battery tires, operating at 50 psi, provide good performance and low rolling resistance at warmer operating temperatures. Further development of battery tires for cold-weather performance will reduce rolling resistance losses.

4. On road traction power required at 0°F is 60% higher than at 70°F. The traction power is indexed to power required at ambient temperature of 70°F. The ratio of power at different ambient temperatures is referenced to 70°F to maintain 55 mph EV speed.

5. Wet versus dry traction power of the EV increases to more than 5% on the wet road. Power required on a wet road to maintain EV speed at 55 mph is approximately 60 mph.

Varying driver profiles impact the EV cold-weather performance as each driver has a different profile. Some drivers are interested in comfort while some of the drivers are interested in distance and performance. The heater accessory power consumption is 1,800 W and the low beam headlights and taillights power consumption is 300 W.

Assuming that the 10 kWhr energy is supplied during the EV driving, at an ambient temperature of 70°F, the compact EV travels 75 miles at 55 mph. Under the same load conditions, the EV travels 50 miles at 55 mph at 20°F. Thus the range of the EV is reduced at a lower temperature.

The battery pack differential—temperature difference—between the ambient and the battery pack is large. In most cases the temperature differential is 15 to 40°C above the ambient temperature. The pack temperature differential is observed to be larger at lower ambient temperatures than at higher ambient temperatures.

The effective battery pack energy diminishes significantly when the Pack Capacity (Whr) tests are conducted at cold temperatures. This is owing to the battery pack temperature and the reduced battery capacity resulting from a higher current draw at higher power requirements. It is important to develop a battery thermal control system to maintain the battery pack temperature within limits.

EV driving range is impacted by temperature. At 55 mph speeds, the vehicle range reduces from 100 miles at 70°F, to 75 miles at 40°F, to 55 miles at 20°F, down to 44 miles at 0°F. This range reduction is due to cold temperature effects on battery pack performance.

When the HVAC system is in use, and the compact size vehicle is being driven at 55 mph, the range reduces to 40 miles. The battery pack in this mode is being maintained at 70°F.

When the HVAC and the Pb-acid battery is under discharge under cold temperature conditions, the range of the EV is reduced to 35 miles at 20°F and 22 miles at 0°F.

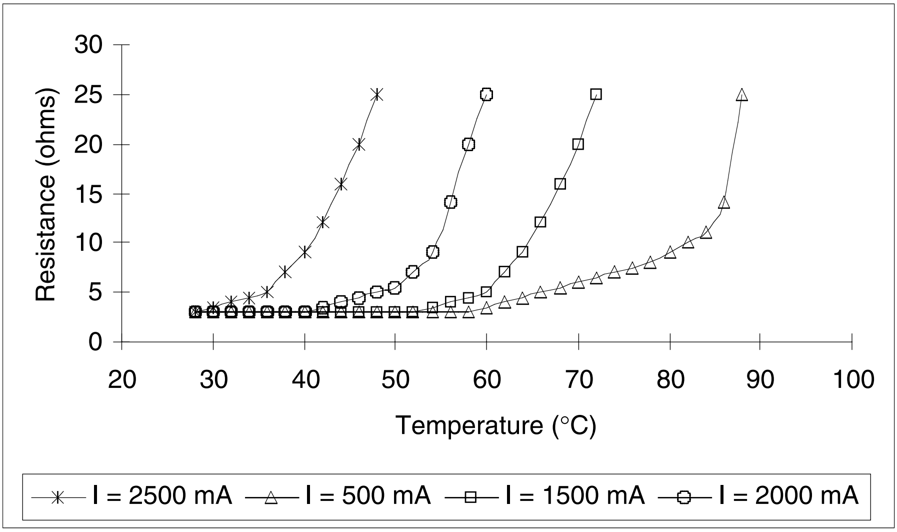
The compact EV has a range of 100 miles at steady 55 mph at an ambient temperature of 70°F. Typically, the vehicle consumes 140 Whr/mile at 70°F for propulsion only. The vehicle consumption increases to to 245 Whr/mile at 0°F (75% more).

Assume a gasoline-powered vehicle gets 30 miles/gallon at 55 mph—that's about 1,100 Whr/mile.

If the compact EV power consumption increases by 105 Whr/mile at 0°F, its efficiency would be reduced only 9% to 27.3 miles/gallon. Engine coolant and exhaust system heat may actually reduce the losses.

The compact EV losses may be broken down into component losses. The drive unit mechanical losses are primarily related to the gear train, while electrical losses are related to the alternating current (AC) motor and power inverter. Battery losses are not included. The other chassis losses are due to drive shaft, residual brake drag, and wheel bearings. HVAC is the heating, ventilation, and air conditioning system using a heat pump.

Figure 7–2 PPTC thermistor profile at varying current densities.



with insignificant rise of battery cell temperature. After 40 minutes, the battery temperature rises at a rate of 11°C/minute. After 44 minutes, the battery voltage and temperature rises. The temperature increase is at a rate of 20°C/minute. The external cell temperature reaches 85°C before stabilizing at 80°C. The maximum cell temperature of 85°C is 30°C below the temperature reached by the battery cell without a PPTC thermistor protection.

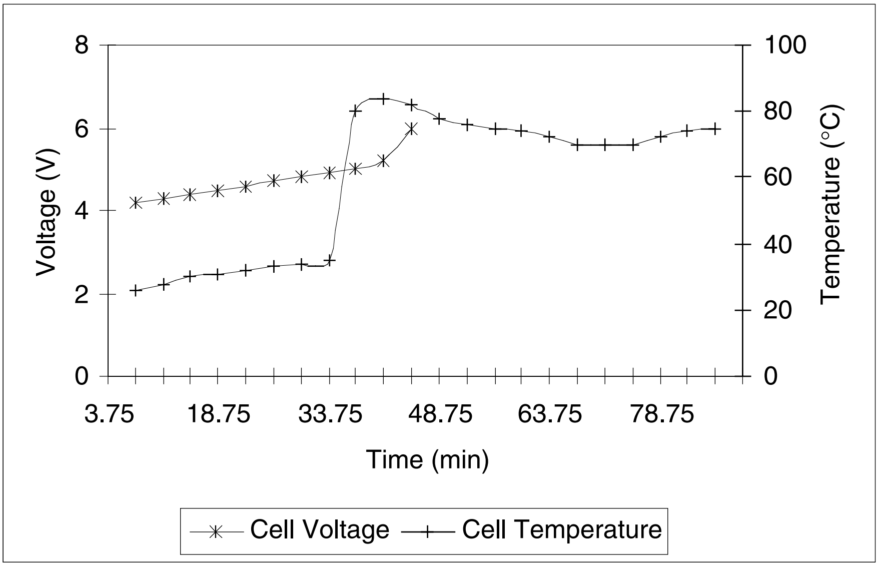
The PPTC thermistor operating at a low temperature limits the charge current close to the functional pack operating temperature as shown in Figure 7–3. The PPTC thermistor resets itself when the battery pack temperature rises, owing to excessive sunlight exposure. This feature prevents the battery pack from being disconnected owing to nuisance tripping at high battery pack temperatures.

The BPMS Charge Indicator

The battery charge indicator or fuel gauge should provide the actual battery capacity and nominal battery capacity readings. This indication is represented as:

- A miles-to-go indicator or a fuel gauge
- An economy range indicator in terms of kWhr/mile or kWhr/km

Figure 7–3 PPTC thermistor voltage/temperature characteristics.



- A warning light or an audible signal for a battery in a dangerous or faulty condition requiring immediate servicing as a "maintenance required" command

This condition should not be capable of being bypassed without a reset and disengagement of the battery pack from the traction controller module. The available energy or capacity of fully formed traction battery can be divided into three portions. The first portion of the capacity is the energy that can be restored or replenished by charging. The second portion of the traction battery energy is the available energy under the present conditions of SOC, discharge, and temperature. The third portion of the traction battery energy is the unusable energy owing to crystalline oxide formation, also known as memory. Both VRLA and NiMH batteries exhibit this memory effect.

While the SOC indicator or fuel gauge is useful, the gauge is reset to 100% each time the battery pack is recharged. The gauge shows a 100% each time regardless of the individual battery's state of health. This leads to a serious miscount of the battery pack energy being shown as 100% after a full charge, when in fact the charge acceptance has dropped down

CHARGING TECHNOLOGY

With EVs comes the EV recharging infrastructure, both for public, domestic, and private use. This charging infrastructure includes recharging units, ventilation, and electrical safety features for indoor and outdoor charging stations. To ensure the safe installation of charging equipment, changes have been made to building and electrical codes.

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During EV charging, the charger transforms electricity from the utility into energy compatible with the vehicle's battery pack. According to Society of Automotive Engineers (SAE), the full EV charging system consists of the equipment required to condition and transfer energy from the constant-frequency, constant-voltage supply network to direct current. For the purpose of charging the battery and/or operating the vehicles electrical systems, vehicle interior preconditioning, battery thermal management, onboard vehicle computer, the charger communicates with the BMON. The BMON dictates how much voltage and current can be delivered by the building wiring system to the EV battery system.

Charging of the battery pack is passing an electrical current through the battery to reform its active materials to their high-energy charge state. The charging process is a reverse of the discharging process, in that current is forced to flow back through the battery, driving the chemical reaction in the opposite direction. The algorithm by which this is accomplished is different for each battery type due to the variations in the batteries' chemical components.

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